Programme Area: Bioenergy

Project: Energy From Waste

Title: Energy from Waste: UK Benefits Case

Abstract:

This deliverable is number 2 of 2 in Work Package 4. It represents the final deliverable for the Energy from Waste FRP, namely the benefits case for Energy from Waste in the UK. As such it addresses
1) The opportunity for Energy from Waste in the UK
2) Makes recommendations regarding Technology Development Opportunities needed to take advantage of the opportunities identified.
The report is based upon the deliverables from each of the preceding work packages:
WP1: UK Waste arisings
WP2: Technology Assessment
WP3: System Modelling

Context:

The Energy from Waste project was instrumental in identifying the potential near-term value of demonstrating integrated advanced thermal (gasification) systems for energy from waste at the community scale. Coupled with our analysis of the wider energy system, which identified gasification of wastes and biomass as a scenario-resilient technology, the ETI decided to commission the Waste Gasification Demonstration project. Phase 1 of the Waste Gasification project commissioned three companies to produce FEED Studies and business plans for a waste gasification with gas clean up to power plant. The ETI is taking forward one of these designs to the demonstration stage - investing in a 1.5MWe plant near Wednesbury. More information on the project is available on the ETI website. The ETI is publishing the outputs from the Energy from Waste projects as background to the Waste Gasification project. However, these reports were written in 2011 and shouldn't be interpreted as the latest view of the energy from waste sector. Readers are encouraged to review the more recent insight papers published by the ETI, available here: http://www.eti.co.uk/insights

Energy from Waste

UK Benefit Case

Report Deliverable 4.2

Prepared for the Energy Technologies Institute

Distributed Energy Programme

July 2011

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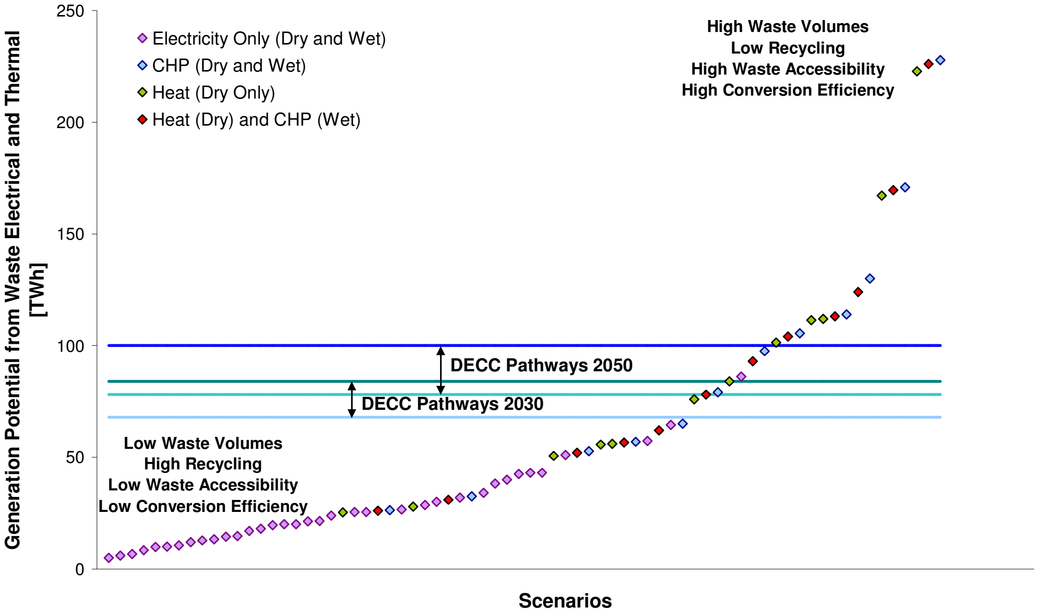
Executive summary

The UK generates over **330 million tonnes of waste per annum**, including over **90 million tonnes that are energy bearing**. Projecting residual waste arisings based on drivers of volumes arising (per capita) and amount of material recycled (or reused), residual waste arisings embedded energy of **500 to 1,000 PJ per year** is projected to be available in the 2030 timeframe.

The proportion of this that can be converted to energy is dependant on a number of factors such as: the amount of residual waste available for energy conversion, and the efficiency with which the embodied energy is converted to useful heat, electricity or other energy vectors. Applying forecast values for low to high waste availability and conversion efficiencies shows that the amount of useful energy from waste (both heat and power), nominally in 2030, ranges from **5 to 230 TWhrs**. The projected achievable **electrical generation is approximately 25 TWhrs per year** equating to **between 5% and 8% of the UK's electricity demand**.

The graph below summarises all the potential energy from waste scenarios developed by the project team during the modelling work. At the low end the chart assumes low waste production, high recycling, low accessibility of waste and low conversion efficiencies. At the high end of the chart the scenario assumes high waste volumes, low recycling and easy accessibility of waste that can be converted at high efficiencies. Both the project team and DECC have looked at likely scenarios. The DECC 2050 pathway results are shown on the chart.



Potential Energy from Waste Availability 2030

The emissions benefits that may result from energy from waste are dependant on the emissions intensity of the emission source that is offset by the energy from waste process, and the emissions intensity of the waste itself. Overall, for each of the technology and waste arisings scenarios, the deployment of advanced energy from waste technologies is projected to contribute to a **net decrease in UK CO_2e emissions of between ~5 and ~10 $MTCO_2$e/year** in 2030 at mid-point technology conversion and waste arisings scenarios. **Greater emissions reductions** are associated with **high total conversion efficiency technologies**, both to electricity and from **utilising heat.**

The commercial and technical assessment of energy from waste technologies carried out in this project shows that dry (around 20% moisture) wastes are currently incinerated at low efficiencies and are economically marginal. In fact, without landfill taxes, LATS and ROCs these technologies would not be economic. If higher conversion efficiencies can be achieved and all available heat can be used in distributed community scale heat and power systems, it is theoretically possible to make significant improvements in the economic case. But the technology readiness level is currently around 5, so significant development work is required to create robust operation on waste feedstocks. Technical barriers relate primarily to effective thermochemical conversion and gas cleaning solutions. However, without high quality system design and technology integration to optimise the total efficiency and operation, including the gas treatment and downstream gas utilisation, value-creating technology will not be developed.

For wet wastes (over 80% moisture), Anaerobic Digestion is becoming established as the preferred technology for food and other biogenic wastes, building on experience in the water sewage treatment industry. However, gas yields are low, and at smaller scales, low economies of scale mean that capital costs are too high.

Integrated waste to energy facilities scaled to communities that maximise the resource efficiency of waste conversion to heat and power for local communities offer potential additional economic and environmental benefits that fit with the UK coalition's localism agenda. They require development and demonstration before public adoption.

If the total wastes arising in the UK are divided by the number of communities at each scenario scale, the number of possible EfW plant opportunities can be identified as shown in the table below.

City	Town	Village	Rural
500kt/yr	50kt/yr	5kt/yr	500t/yr
76	946	4,544	4,544

Number of UK plants for each community scale

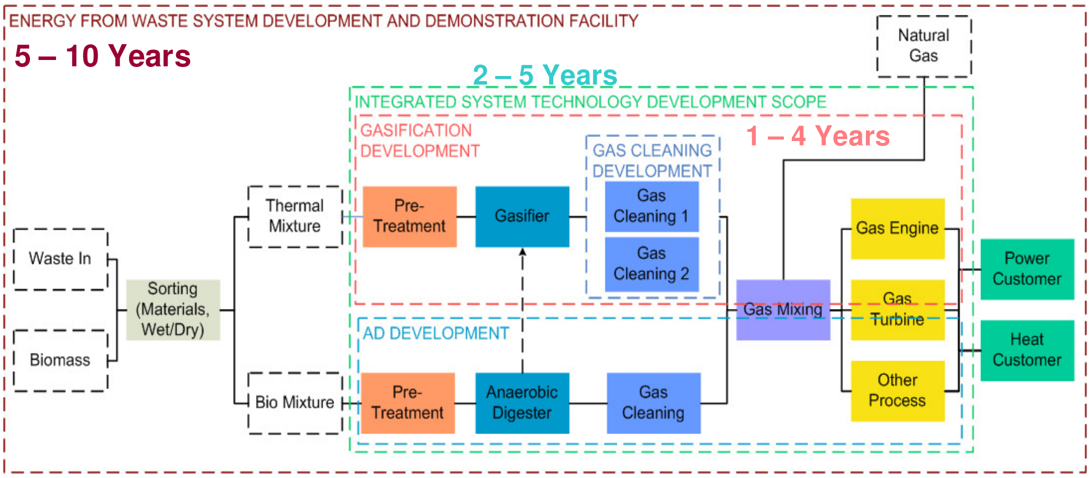
The testing, modelling, technology assessment and integration work done in this project leads to a small number of areas that are attractive technology development opportunities for the ETI. Specifically, these are:

- The development of integrated advanced thermal (gasification and pyrolysis) systems for energy from waste at the community scale. City scale technology is well served and the focus on the development work should be on town and village scale technologies.
- Cost effective gasification gas clean-up is a special case as this is essential to the development of community scale gasification systems.
- Low cost, high efficiency distributed scale anaerobic digestion (AD) plants that can be integrated with advanced thermal technologies.
- The development of community scale integrated distributed energy from waste facilities link thermal and AD technologies into highly efficient systems that can maximise resource efficiency.

Four potential ETI projects have been identified by the project team and are described in detail in this report. Potential costs of the projects are summarised in the table below:

Programme	Capital	Project Costs	Timescale	Priority
Advanced Thermal Processes	£10m - £15m	£10m	3-5 years	1
Gasification Gas Cleaning	£5m	£3m	2-3 years	2
Anaerobic Digestion	£3m	£2m	3-5 years	3
Integrated Facility	£15m - £20m	£5m - £10m	3-6 years	4
Total	£33m - £43m	£20m - £25m		

The diagram below shows how the four stand-alone projects integrate into a development programme for the demonstration of an integrated systems approach to energy from waste.



In addition, the project identified further developments that could add increased value in the future. These are low cost heat networks; processes to covert syngas into chemicals or fuels; and the pyrolysis of segregated materials for liquid fuel production. All are potential areas of opportunity to increase the value of the core technologies recommended for development. These opportunities were validated by the ETI's Energy from Waste technology stakeholders on the 6th of June 2011, where the consortium and the ETI were guided to the **value for the energy from waste and thermal processing industries from the ETI supporting further development in the integration of gasification systems.**

The project team is proposing an approach to innovation that does not prescribe a specific technology solution, as the nature of research and development projects in this market space makes defining the achievable efficiencies unrealistic. Instead it is proposed that a range of likely attainable technology attributes for the technology conversion efficiency, capital and operational costs (excluding feedstock) are targets. These are summarised for advanced thermal and anaerobic digestion technologies in the tables below.

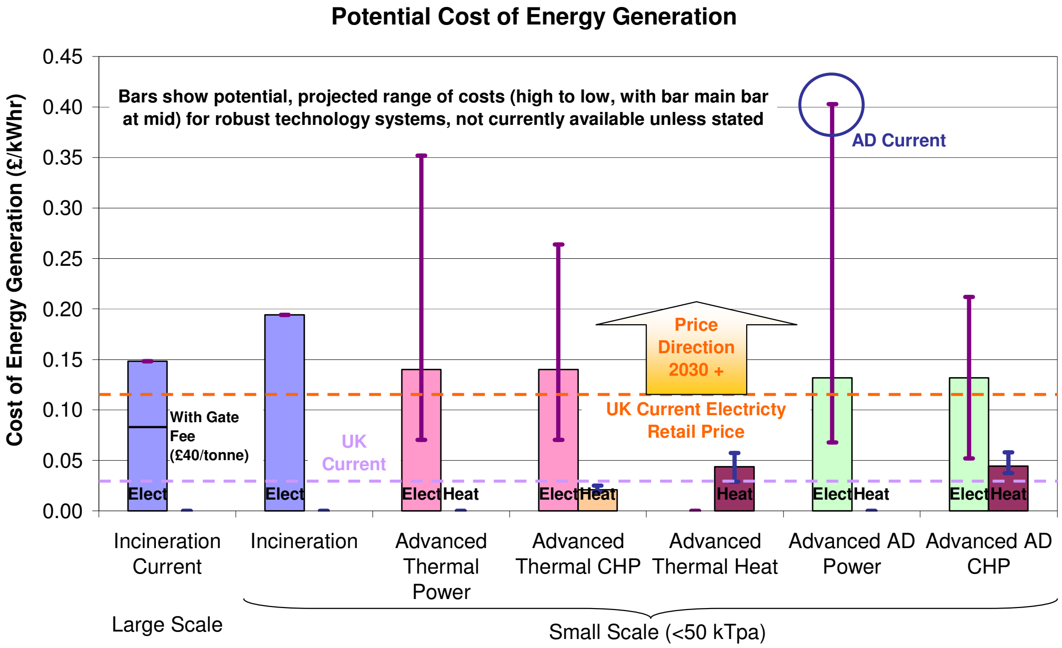
		Low	Middle	High
Capital Cost [£/tpa]	Electricity	350	500	650
	Heat	100		
Operational Cost [£/kWhr]	Electricity	0.02	0.05	0.1
	Heat	0.01		
Conversion Efficiency [%]	Electrical and Heat	30%	38%, 50%	80%
	Waste Feedstock Mass Conversion	50%	65%, 80&	100%

Projected and Assumed Values Impacting Cost of Energy
(Advanced Thermal Conversion Technologies)

		Low	Middle	High
Capital Cost [£/tpa]	Electricity	100	150	200
	Heat	100		
Operational Cost [£/kWhr]	Electricity	0.02	0.05	0.1
	Heat	0.01		
Conversion Efficiency [%]	Electrical and Heat	30%	33%	35%
	Waste Feedstock Mass Conversion	17%	30%	45%

Projected and Assumed Values Impacting Cost of Energy
(Advanced AD Technologies)

Since defining the absolute achievable efficiencies is unrealistic, the consortium recommends a system based approach to energy from waste technology research and development to maximize the energy generation potential with a focus on their commercial viability. Currently, technical barriers exist to the robust deployment of small scale (≤ 50 kTpa) energy from waste technology. This project has identified these barriers, and projects that **conversion efficiencies** of **30% for dry waste** and **15% for wet wastes** are achievable following targeted technology development, which the ETI is well placed to fund. As illustrated in the chart below, if the technical barriers were to be overcome as a result of ETI funded development work, **energy generation costs** from waste (without a gate fee) for the middle scenario are projected to be ~**£0.14 /kWhr**. This is a **reduction of £0.05 /kWhr** as compared to the current state of small scale incineration technologies, and is projected (mid point), to equate to a **UK annual savings of £1.25BN.** Compared to large scale incineration, the annual saving is projected to be £500M.



Projected Costs of Energy Generation (electrical and thermal) following technology Development

The **in-depth technical, economic and emissions assessment** carried out in this project has shown the opportunity for energy from waste to contribute to the UK's emissions reduction by between **5 and 10 MT CO_2e/year**, to supply around **25 TWhrs** of secure electricity and at an electrical generation cost of approximately **£0.14/kWhr**, and could achieve **UK energy from waste cost savings of £1.25BN per year.** The investment for the UK to realise these benefits is projected to be around **£12BN**, which is aligned to Defra's and the waste industry estimate that between £11BN and £18BN of investment will be required by 2025 to meet the EC Landfill Directive. To achieve these benefits, considerable technical development and demonstration are required, especially around the end-to-end waste to power generation system integration of advanced thermal conversion (gasification) technologies. Its collaborative structure and ability to bring together a range of cross-disciplinary skills **uniquely positions the ETI to enable the successful development and demonstration of energy from waste systems.**

1 Introduction

1.1 The challenge

The UK generates over 330 million tonnes of waste per annum (see Figure 1); including over 90 million tonnes which are energy bearing. Direct emissions from the waste management sector in the UK accounted for 3.2% of the UK's total estimated emissions of greenhouse gases in 2009, or 17.9 Mt CO_2e[1]. Government legislation is seeking to incentivise the diversion of waste from disposal in landfill through the landfill tax and landfill diversion targets (1999/31/EC)[2,3]. In parallel, the UK is committed to reducing its greenhouse gas emissions by 80% by 2050 and supplying 15% of its energy demands from renewable sources by 2020.[4] These requirements are driving the need for technology solutions, which enable residual wastes to be used as cost-effective, low carbon and indigenous energy resources.

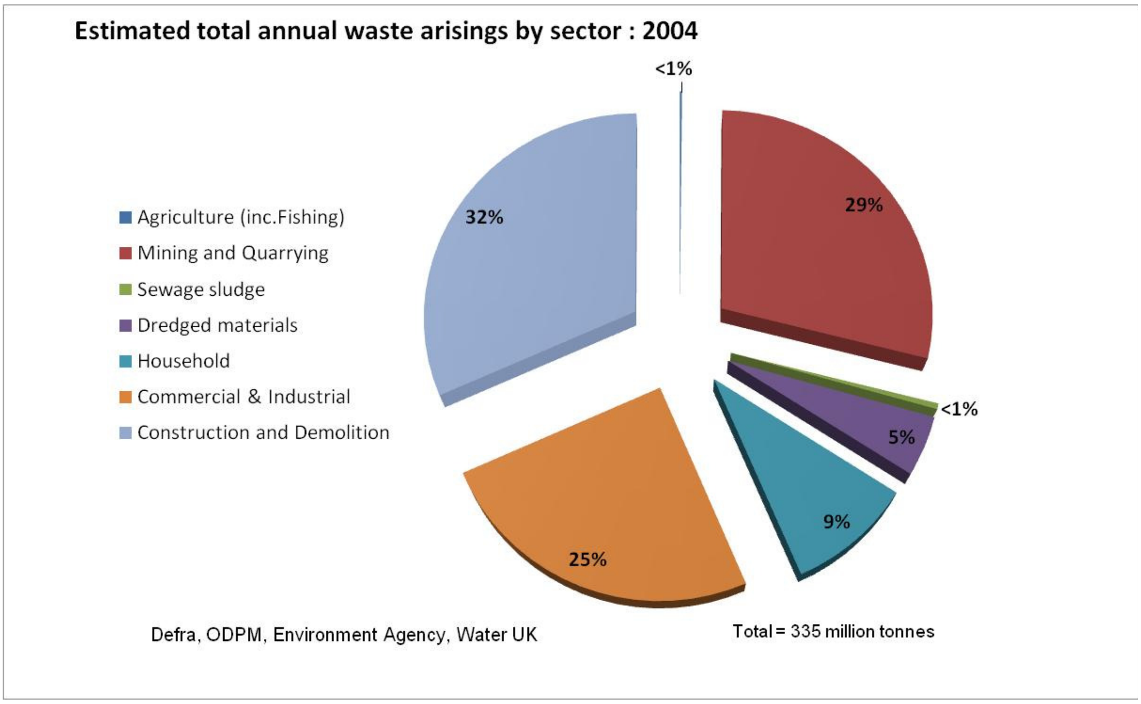


Figure 1 UK waste arisings 2004

The UK government's waste management approach is driven by the adoption of the waste hierarchy in the EC Waste Framework Directive (see Figure 2). A series of initiatives have been established to implement the UK's waste priorities. The Landfill Directive sets:

- Minimum standards for the location, design, construction and operation of landfills;
- Targets for diversion of biodegradable municipal waste from landfill; and
- Controls on the nature of waste accepted for landfill.

The use of landfill has been discouraged across the UK through various financial

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[1] http://www.defra.gov.uk/environment/waste/, 22/06/2011

[2] Scotland's zero waste plan, The Scottish Government (2010). From http://www.scotland.gov.uk/Publications/2010/06/08092645/11

[3] Waste strategy for England (2007). Defra, London.

[4] Going to waste: Making the case for energy from waste, Confederation of British Industry (2010).

and voluntary instruments including:

- Landfill tax – currently levied at £48/tonne (+VAT);
- Landfill diversion targets for local authorities managing MSW;
- Initiatives to encourage waste recycling and reuse; and
- Initiatives to encourage energy from waste programmes.

Current knowledge of wastes, and the opportunities to control the disposal path is greatest for MSW, with C&I wastes only exposed to the economics of market forces and the landfill tax instrument to cause material diversion. Evidence of technology opportunities has contributed to the waste industry increasing its technology investment and material diversion potential. The Department for Environment Food and Rural Affairs (DEFRA) estimates that £11bn of investment is still required to meet the final diversion targets with established confidence in technology performance and planning acceptance.

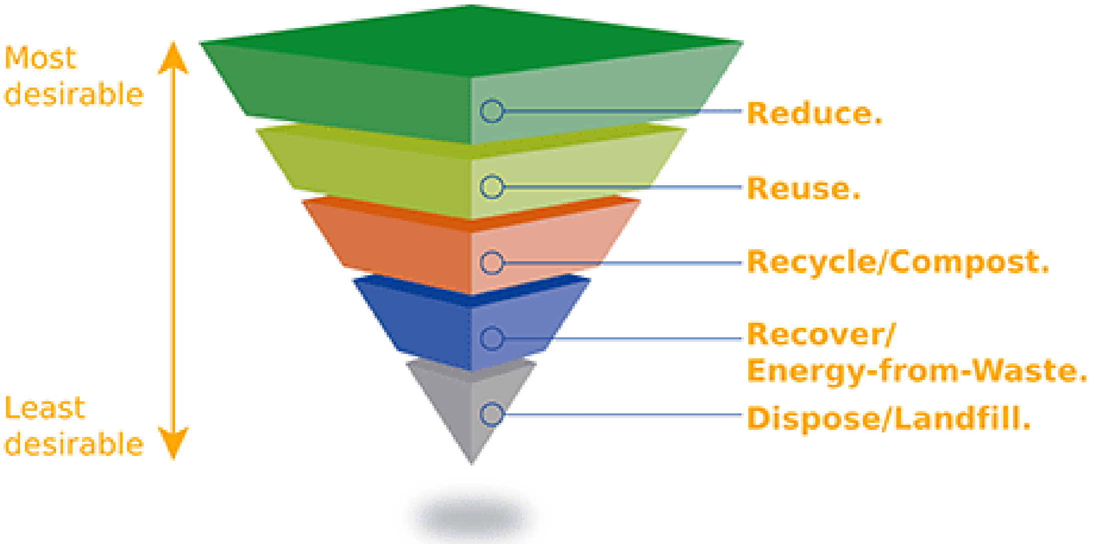

Figure 2 The Waste Hierarchy

Adoption of the waste hierarchy approach is leading to a reduction in the generation of wastes and an increase in the extraction of materials with an alternative commercial value. This means that the amount and nature of waste generated is changing over time and any generic EfW process must have the ability to cope with the changes. In addition, waste volumes and their composition including moisture content are factors central to consider when determining the opportunities for EfW.

1.2 Energy security and robustness

The UK has around 76GW (gigawatts) of electricity generation capacity to meet annual consumption of about 350TWh (terawatt hours) and winter peak demand of about 63GW.[5] This level of capacity is roughly 20% higher than the expected level of peak demand. The UK has a diverse electricity generation mix. In 2006, 36% was generated by gas-fired power stations, 37% from coal, 18% from nuclear, and

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[5] Meeting the Energy Challenge, Department of Trade and Industry (2006)

4% from renewables. The remainder comes from other sources such as oil-fired power stations and electricity imports from the continent. Additionally, the UK consumes around 600 TWhrs of energy in the form of heat annually from gas and oil. Crucially, 80% of the UK's energy sources are imported.

Each person in the UK produces about 1 tonne of MSW per year and contributes to about 0.8 tonnes of C&I wastes. These sources of waste amounted to around 90 million tonnes in 2009. Currently, large quantities of Solid Recovered Fuel (SRF), formed from residual waste, are exported from the UK to fuel energy generation and industrial facilities in Europe. If all current residual waste were to be utilised for energy generation, this project estimates that around 50 TWhr of electrical power could be generated annually, in addition to over 110 TWhr of heat[6]. This project has assessed the drivers for residual waste arisings, and has projected high, medium and low volumes suitable for energy from waste in the future. The mid projection is approximately equal to the current arisings volumes. The low and high projections, combined with indicate that between 40 and 86 TWhrs of electrical energy could be generated from indigenous wastes.

This assessment shows that **waste is projected to be able to supply between 5% and 8% of the UK's electricity demand**. Additionally, successful deployment of energy from waste technologies could enable many markets including biomass conversion, H_2 fuels, and the future fuels/chemicals markets due to the versatility of the output gas stream from gasification.

In all cases the use of indigenous waste resources for heat and power generation potentially offsets the import of fuels, aiding energy security. In this respect, the greater the use and efficient conversion of waste to useful heat and/or electrical energy, the greater is the offset of other forms of energy, and hence the greater the impact on national energy security. For distributed resources, such as waste, system efficiencies are greatest (minimal transportation and energy distribution losses) when technologies are suitably scaled to coincide with the resource arisings, enabling the effective use of all the energy available, both electricity and heat.

In addition to having a high conversion efficiency, energy from waste technology systems need to be robust and reliable, particularly with varying waste streams, in order to provide both energy and waste management security. Whereas other fuel resources are relatively benign may be stored, waste degrades rapidly when stored, causing local environmental issues.

To enable waste resources to make a positive impact to emissions reduction and energy security requires highly efficient, robust conversion technologies for both dry and wet waste streams. This project seeks to identify the current state of the technology, and to investigate the potential for, and impact of, development in the technology to increase the benefits of energy from waste.

1.3 Project aims

The Energy Technologies Institute (ETI) commissioned a consortium (Caterpillar, Centre for Process Innovation (CPI), Cranfield University, EDF Energy and Shanks Waste Solutions) in July 2009 to examine the technology development

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[6] Assumes electrical conversion efficiency of 30% for dry waste, 15% for wet waste, 80% (total electricity and heat) conversion of dry wastes, as detailed in Section 5.

requirements for fuel flexible heat and power generation systems capable of operating on a range of wastes through its EfW Flexible Research Projected (FRP). This project was commissioned within the ETI's Distributed Energy (DE) programme due to the synergies of scale of waste arisings, and the efficient and effective use of the generated power, nominally in the range of 1 to 10 MWe (and associated scale of heat). The aims of the project were to provide:

1. Detailed analysis and characterisation of UK waste arisings;[7]
2. Assessment of the available EfW technologies;
3. Identification of combinations of technologies for developed and related technology development opportunities;
4. A clear UK Benefits Case for the development and deployment of the identified technologies; and
5. Sufficient data generated, compiled, analysed and presented to enable the ETI to make decisions at the end of the project regarding future programme scope.

The project has been delivered through four interconnected work packages (WPs) covering waste assessment, technology assessment, technology performance and modelling, and the UK Benefits Case (see Figure 1.3).[8]

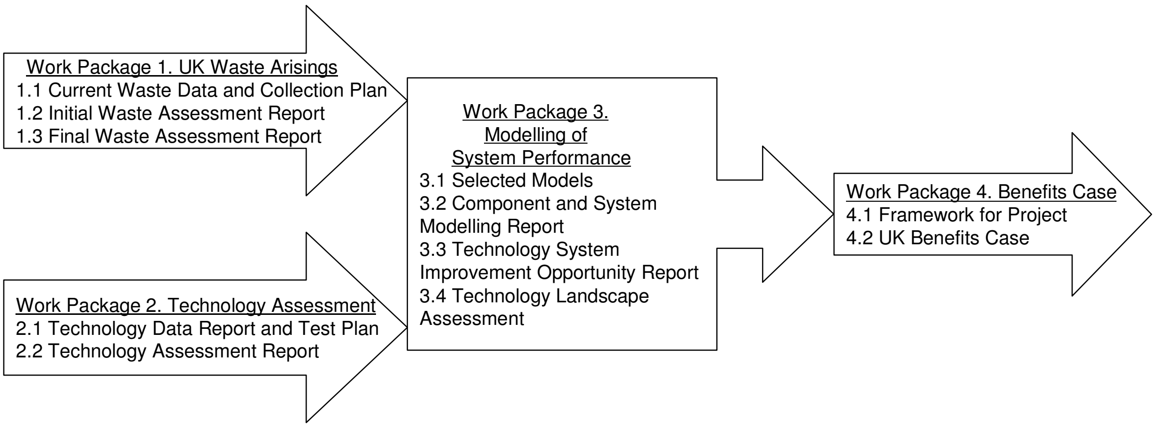

Figure 3 Project structure and Work Packages

1.4 Key findings from Work Packages

The first WP, (UK Waste Arisings) was led by Cranfield University and provided a representative summary of waste as a resource. The consortium reviewed the quality of available data in line with waste volumes and energy value (see Table 1). This led to waste sampling and assessment, concentrated on commercial, industrial and demolition wastes in order to establish sufficient data in these areas.

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[7] The geographic mapping of these wastes is being carried out as an associated project, separate to the main scope of this work.

[8] See **Appendix A** for a summary of the aims, methodology and conclusions from the four WPs.

Sector type vs data	Ag	M&Q	SS	DrMt	MSW	Com	Ind	C&D
	<1%	30%	<1%	5%	9%	11%	13%	32%
Energy	H	L	H	L	H	H	H	M
UK Arisings	L	H	L	M	M	H	H	H
Data Quality	M	M	H	L	H	L	L	M

Table 1 UK waste arisings, data quality and potential energy content[9]

The waste sampling regime was carried out at a number of Shanks operated sites. Each site was sampled twice each season over a four season, twelve month period. A detailed hand sort of the waste was carried out and images taken for visual composition analysis. At least one sample from each detailed sort was sent to an external lab for proximate and ultimate analysis to determine properties such as moisture content, calorific value (CV) and elemental composition. This analysis showed that **although waste varies in its form and type (material composition), it is largely constant in its overall elemental chemical composition**, as shown in Table 2. The major variable was found to be the moisture content, which varies seasonally with the weather. It has a major bearing on the gross CV of the mixed materials. It was found that the moisture free, elemental composition of the waste averaged to $CH_{1.4}O_{0.65}$. The ratio of Carbon, Hydrogen and Oxygen is similar for biomass (the energy being a function of the amounts of Carbon and Hydrogen present). This averaged composition has been used to represent mixed waste in the modelling work carried out for WP3 of this project.

Weight % basis	Average	Standard Deviation	Battelle Technical Paper[10]
Carbon %	49.4%	0.052	45.52
Hydrogen %	5.6%	0.015	5.75
Nitrogen %	1.5%	0.015	0.29
Oxygen %	42.8%	0.051	37.79
Sulphur %	0.3%	0.004	0.19
Chlorine %	0.4%	0.005	0.43 to 1.54

Table 2 Average elemental composition of waste samples (moisture free)

The waste volume and composition data gathered from the sampling regime was combined with available literature data to collate the mass and composition on current arisings. In order to project likely future arisings, consideration was made for the removal of materials with a commercial value from these streams, as might be dictated by their commodity value and/or recycling legislation.[11] In all cases, limitations in sorting practices and recycling iterations (i.e. the number of times a material can be recycled into a useful material) means that a considerable volume of residual energy bearing waste materials are expected remain arising in the

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[9] Ag- Agricultural; M&Q- Mining and Quarrying; SS- Sewage sludges; DrMt- Dredging materials; MSW- Municipal solid waste; Com- Commercial; Ind- Industrial; C&D- Construction and demolition

[10] Battelle Technical Paper reference. Gasification of Refuse Derived Fuel in a High Throughput Gasification System. Mark A Paisley, Robert D Litt, and Kurt S Creamer (1990).

[11] This analysis was carried out by AEA and is outlined in Deliverable 1.2 with further assessment of the commodity price effect on volumes in Deliverable 3.3 (see **Appendices**)

future, projected to be between 70 and 130 million tonnes by this project in 2030.

The second WP (Technology Assessment) was led by Caterpillar with input from Cranfield University and EIFER (research subsidiary of EDF Group). WP2 assessed how the waste streams identified in WP1 behaved in a number of EfW technologies. This work identified significant development opportunities to increase the conversion potential and/or efficiency of the technologies. In parallel, a review of potential legislative and planning requirements triggered by deployment of the technologies was undertaken by AEA technology.[12] Technology testing was carried out by Cranfield University on thermal (gasification/pyrolysis) technologies suited for dry wastes and by EIFER on AD for high moisture content food, paper and card wastes. These tests were complemented by in-kind testing carried out by Caterpillar in the use of typical clean gasification-derived gases in a gas engine. All the technologies tested were selected for examination due to their potential to contribute to high energy recovery efficiency systems as detailed in Deliverable 2.1.

In general, the conversion technologies were found to be operable with a range of material mixtures representative of mixed waste streams. The need to handle mixed wastes, with varying moisture content and form, led to the focus on fluidised bed gasifiers for general use and downdraft gasifiers for smaller scales for the thermal technologies. These technologies were down-selected based on the testing of waste mixtures and literature evidence, as they should provide a more reliable, cleaner fuel from a wide range of waste compositions once the pre-treatment, process optimisation and gas clean-up challenges have been resolved. Although slow pyrolysis may be appropriate in certain circumstances where an oil product and residual biochar have a value, flash pyrolysis was not studied in the treatment of MSW and C&I waste due to the requirement for a well characterised, segregated waste stream (which was outside the scope of examining robust technologies for variable, mixed wastes in this project). Pyrolysis routes that produce gas or are combined with gasification steps were considered as “advanced thermal processes”, alongside gasification, in subsequent analysis due to the similarity of the processes.

The third WP (Technology Performance Modelling and Assessment) was led by the CPI and assessed technology performance through empirical modelling. Due to limitations in availability of component cost and performance data, technical modelling of energy from waste systems was supplemented by community scenario based assessment of the high level costs and emissions associated with different waste processing options at city, town, village and rural scales. The community scenario data was informed by the earlier component modelling and waste arisings data from WP1, and were verified at an ETI workshop in November 2010. The assessment of the community scenarios led to the identification of future development options and formed the basis of the component technology development and the macro financial and cost models developed in the fourth WP[13].

Most UK communities produce tonnages of MSW that are less than the current minimum economic scale for incineration and gasification plants of around 500 kT/yr. Smaller scale communities, which produce 50kt/yr of MSW down to less than 500t/yr, represent a significant technology development opportunity. Currently,

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[12] See Report D2.2 from WP2. Also see the AEA report in **Appendix B** which covered current and future policies, legislation and regulation that could influence the deployment of EfW schemes in the UK.

[13] See Report D3.3 from WP3. Also see **Appendix C**.

smaller scale, integrated advanced energy from waste systems (including incineration, gasification and pyrolysis) are not technically viable at these scales. As the efficiency of electricity production from current gasification and incineration technologies is around 20%, a significant amount of the potential energy content of the waste is lost. Distributed EfW plants, of an appropriate size where 'waste' heat can be used for local community CHP, would bring significant benefits in efficiency and reductions in transport costs and CO_2. The economic viability of EfW plants is inextricably linked to the cost of the feedstock, the capital cost of the plants, the efficiency of conversion of the waste to useful energy, the product value and the local use of waste heat. As a result, these were the metrics that were evaluated subsequently in the project.

This report is the outcome from the fourth WP (UK Benefits Case), which was led by EDF Energy. The assessment carried out for this report collates the preceding WPs outputs to develop the community scale scenario assessment for the calculation of the UK CO_2 emissions and EfW infrastructure costs (affordability) for the UK Benefits Case. Two external consultative studies were also commissioned within this work package to further inform the outcomes and recommendations, as detailed in the body of this report.

1.5 Report structure

This report, the Benefits Case, brings together and examines inputs and findings from the four WPs. The results and findings are based on a comprehensive modelling and scenario analysis on how EfW technologies can be used to meet waste and carbon reduction needs.

The remaining part of this report is structured as follows:

Section 2 presents a summary of waste arisings and a framework of community scenarios to test the EfW technologies

Section 3 focuses on the data and findings from the modelling in relation to affordability and CO_2 reductions.

Section 4 assesses the current state of the technology, based on technical merit and their associated economic performance.

Section 5 brings together a number of inputs from the WPs to assess the technology development opportunities in relation to specific EfW technologies.

Section 6 assesses the cost of energy generation from the technologies in their proven, developed state based on an assessment of a range of performance and economic levels that the developed technology might achieve.

Section 7 draws together the analysis and makes some recommendations to the ETI on future demonstration projects.

A Bibliography and list of references is provided to support the findings in this report. The Appendices are included in a separate document and include a summary of the WPs, copies of the parallel reports prepared by AEA and CARE, and user instructions for the affordability and CO_2 reduction model.

2 Energy from Waste Scenarios

2.1 Community scales[14]

The average UK resident contributes to around 1.8 tonnes of waste per year, which is mainly made up of MSW, C&I waste and wet wastes[15]. In total there is around 90 million tonnes of energy bearing waste arising in the UK each year, with an average calorific value (CV) of 10 GJ per tonne. If the average CV of the energy containing wastes is 10 GJ per tonne and if 50% (assuming high collection efficiency) is converted to usable energy at 70% efficiency (assuming a high proportion of CHP) waste could produce around 50 TWhrs annually. This equates to around 3% to the UK's energy requirement. In the DECC 2050 UK Energy Pathways Analysis it is assumed EfW will be more than 1% of UK energy demand.[16]

The distributed nature of waste arisings and their modest energy density suggest that EfW will be most beneficial in cases where local distributed solutions can be created. However, at smaller scales (< ~50 kTpa), incineration (with energy recovery) becomes inefficient due to reducing efficiencies of the energy recovery steam cycle. This leads to the requirement for scalable, efficient and cost effective technology to support the estimated 4000 – 10000 "local" facilities possible within the UK. Advanced technologies, such as Mechanical Biological Treatment, capable of processing waste materials are also likely to be able to handle biomass and other feedstocks and support further power generation capacity. Four EfW technologies (gasification, pyrolysis, incineration and AD) were tested against the average waste composition for four population scenarios (see Table 4). The scenarios were based on representative sizes of typical UK communities and aimed to:

- Develop the waste scenario for each case;
- Assess the technology options that can process the wastes to deliver the most effective financial and environmental contribution to the community's energy requirement;
- Identify the technology developments that can improve the energy from waste supply; and
- Bring the data together into a potential technology development plan with options for future funding.

The scenarios represent the scale of EfW plants required to meet local energy needs. Currently, most effort is targeted at cities despite 64% of the UK population living in towns or villages. Therefore, there are significant EfW opportunities in developing low carbon energy supply systems for towns and villages.

For simplification, three major assumptions were made:

- The technologies will be taken up by communities that can use them;
- Waste is used for energy in the locality in which it arises; and
- There will be no planning constraints affecting the EfW developments.

All of these assumptions represent a significant change from the current norm, but it is likely that changes in behaviour will occur in the future.

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[14] Taken from WP 3.3 Report.

[15] See Report D1.3 from WP1.

[16] 2050 Pathways Analysis, July 2010, DECC (2010).

2.2 Waste Arisings

Work Package 1 identified that the main drivers for residual waste arisings are the volume generated and the amount of material removed for reuse/recycling. The volume generated is in turn dependant on social aspects (both at an individual and national level) such as the “willingness” to generate waste and wealth, and the total population. Legislative aspects and external commodity values drive the removal of material from the raw waste stream. The subtlety here is that the legislative framework essentially provides an artificial commodity price floor.

To predict a range of residual waste arising scenarios, the drivers of arising volume change (per capita) and level of recycling were applied to the current waste volumes from Work Package 1. The assumed levels of each of the drivers are set out below in Table 3. For the volumes, the values relate to a % change from current values, with a nominal time horizon of 2030. For the “recycling” values (incorporating re-use), the values are absolute proportions of material that are removed from the raw waste streams, with the “same” value being the average current proportion of material recycled.

Waste Category	Volumes			Recycling		
	Grow	Same	Shrink	Grow	Same	Shrink
MSW	40%	0%	-40%	70%	40%	20%
C&I	40%	0%	-40%	70%	40%	20%
Ag	40%	0%	-40%	70%	20%	0%
Sewage	0%	0%	0%	0%	0%	0%

Table 3 Waste Arising Projection Drivers - Assumed Values (Per Capita)

The distributed nature of waste and potential system level efficiencies of utilising waste for energy near to its source aligned this project to the ETI’s Distributed Energy programme. To further align to potential scales of waste arising, the waste arisings projections (per person) were broken down by 4 community scales of “City”, “Town”, “Village” and “Rural.” Each of these scales was allocated a nominal population, and a high level analysis was carried out as to how these relate to the current demographic of the UK. This data, and the associated range of waste arisings projection (both in mass and embodied energy), is summarised in Table 4. The waste has been split by type (dry and wet) for suitable process option identification. The main value for each waste type by each community scenario denotes the current value, with the high and low range for 2030 included in parentheses. An additional assumption was made that the rural scale produced a larger amount of wet waste from a greater amount of agricultural activity, which was assumed to be 20 kT/year for all scenarios.

Scale	**UK Context**				**Waste Arisings**				
	Population	Percentage of UK population	Number in the UK	Activity	Dry Waste (kT/yr)	Dry Waste Energy Content (MJ/yr)	Wet Waste (kT/yr)	Wet Waste Energy Content (MJ/yr)	Commentary
City	500K	34	5 cities over 500k 26 between 200k and 500k e.g. Leeds	Residential, industrial and service	490 (306-673)	$4.8x10^{9}$ ($4x10^{9}$-$5.6x10^{9}$)	408 (255-560)	$9.2x10^{8}$ ($7.7x10^{8}$-$1.1x10^{9}$)	Urban with little agriculture
Town	50K	43	A few hundred towns e.g. Corby	Residential and commercial with light industrial	49 (31-67)	$4.8x10^{8}$ ($4x10^{8}$-$5.6x10^{8}$)	41 (25-56)	$1.0x10^{8}$ ($8.7x10^{7}$-$1.2x10^{8}$)	Residential and commercial
Village	5K	21	Over 1 thousand villages	Mainly residential	4.9 (3.1-6.7)	$4.8x10^{7}$ ($4x10^{7}$-$5.6x10^{7}$)	4.1 (2.5-5.6)	$1.1x10^{7}$ ($9.7x10^{6}$-$1.3x10^{7}$)	Residential with little commercial
Rural Agriculture	500	2	Very large number of communities	Mixed farming and residential	0.49 (0.31-0.67)	$5.1x10^{6}$ ($4.3x10^{6}$-$5.6x10^{6}$)	20	$6.0x10^{7}$	Mainly farming with little residential

Table 4 Community Scales and Waste Arisings

By aggregating populations over cities, towns, villages and rural scales, a waste embodied energy content range of **500 to 1,000 PJ per year** is projected to be available in the 2030 timeframe. The waste data, and future arisings assumptions summarised in Table 4 and incorporated in the project spreadsheet models are dynamic, and can be updated should further evidence on current arisings or future projection (e.g. from DEFRA) become available. The community scale data was scaled by the number of each of those communities occurring in the UK (based on population density data), to assess the UK potential for the amount of energy that could be generated from dry and wet wastes.

2.3 Energy from Waste Potential

The amount of energy which could be generated from the total residual waste arisings is dependant on the amount of that waste actually used to generate energy ("accessibility"), and the total efficiency with which the energy in the waste is converted to useful energy ("conversion efficiency").

To project the potential for energy from waste in 2030, values of for waste accessibility were assumed of:

- 100%
- 75%
- 50%
- 25%

Conversion efficiency of the total input energy to usable heat and/or power is strongly linked to the conversion technology. The premise of this project is to determine the development needs and opportunities for these conversion technologies. As a result, the values used to assess the opportunity for energy from waste include both current technologies, and those that can be delivered through the development of the advanced conversion technologies detailed in Section 4. These values are related to system level conversion efficiencies (feedstock in to usable energy out) in Table 5.

Conversion Efficiency Values	Thermal (Dry Waste)	Biological (Wet Waste)
Representative of low conversion efficiency	15%	5%
Representative of current best practice	20%	10%
Representative of potential high conversion efficiency	30%	15%
Representative of CHP conversion	80%	20%
Representative of primarily heat recovery with CHP of wet wastes	80%	30%

Table 5 Technology Energy Conversion Efficiency Projections

An additional value of 100% conversion efficiency was applied to the 100% accessible waste arisings to assess the total potential energy within the waste.

The total amount of usable energy that could be generated from waste was assessed by the addition of the projected energy values associated with each combination of accessibility and conversion efficiency factors applied to the range of dry and wet waste arisings projections. The range of values of the energy which could potentially be generated from waste, depending on the arisings and conversion efficiency assumptions applied, are illustrated in Figure 4. The DECC 2050 Pathways scenarios are superimposed on this chart for comparison.

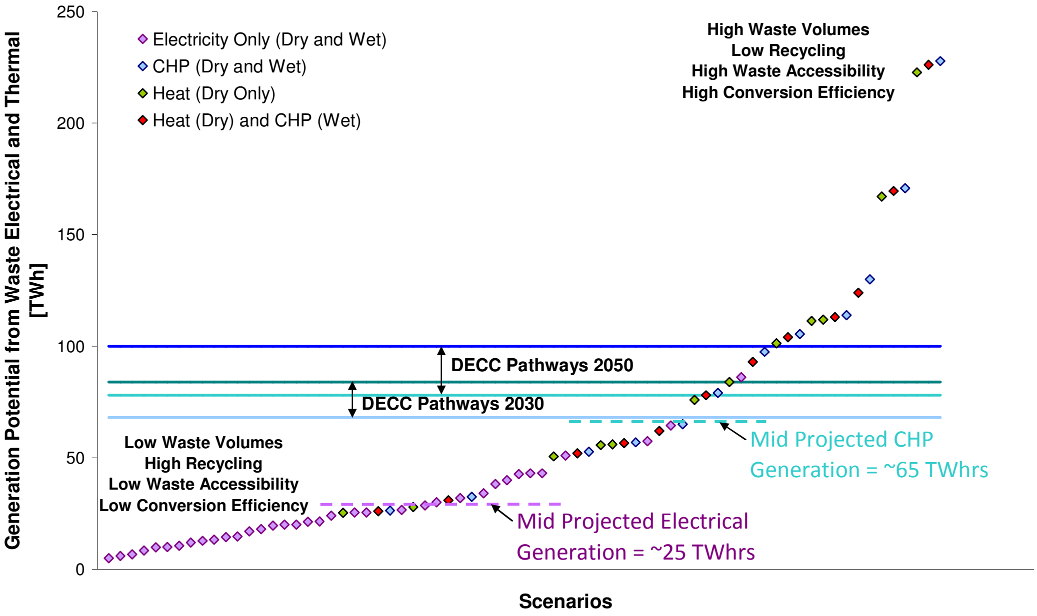

Figure 4 UK 2030 Total Energy from Waste Potential Scenarios

Based analysis shows that the UK could theoretically generate between ~**5 TWhrs and** ~**230 TWhrs** of usable energy from waste in 2030. A mid case, based on central assumptions around waste arisings, accessibility (for energy from waste) and conversion efficiencies, equates to a projected annual generation of ~**25 TWhrs of electrical energy** from waste. As well as being highly dependant on the volume of waste created, the potential for energy from waste is strongly related to the conversion efficiency, and hence technology capability in this respect.

2.4 Economic Impact

The potential opportunity from energy from waste for the UK can also be equated into an economic impact assessment. The projected energy from waste potential mid case of 25 TWhrs/year equates to a generation capacity of 3GW, or 3,000MW, based on a yearly operation of 8,000 hours. At a projected capital cost of £4M / MW (as referenced in Section 6), this equates to a required investment of £12BN. Defra and the waste industry estimate that between £11BN and £18BN of investment is required for the disposal of residual wastes by 2025 to meet the EC Landfill Directive. In line with this projected investment requirement, this analysis shows that the energy security and emissions reductions benefits may be maximised through **maximising the total conversion efficiency** and **minimising the technology costs.**

2.5 Technology Assessment

Data from the project Work Packages has been used to develop the technology system flow sheet in Figure 5, taken from Deliverable 3.3. The model allows for the high-level analysis of the community scenarios and the assessment of emissions and cost benefits which may be derived from future technology developments. The modelling calculated high level figures for CO_2, ash and char produced by the processes but did not forecast the production of other contaminants to air and water. These data formed the basis of the detailed assessment of carbon emission data in Section 3 of this report. A number of general observations can be made:

- Thermal processes – both gasification and incineration – produce significant amounts of CO_2, as both are fundamentally combustion processes either directly or through subsequent combustion in a heat or power conversion device. However, this CO_2 may be accounted for in different ways, as discussed in Section 3.
- The use of local distributed EfW systems that use locally arising wastes reduce the need for transport and can have a significant beneficial effect on local energy security.
- The use of waste heat from all types of EfW technology has major impact on reducing emissions. Using the heat produced during electricity generation raises the overall process efficiency. If this heat could displace natural gas significant reductions in carbon emissions occur.

The input data from waste arisings, the community scenarios and model were used to develop flow sheets and simple economic models. The model assesses the transformation of waste arisings into energy, fuels, chemicals and by-products to show the scale of operations required for each community. No correlation has been carried out between the community's energy demand and the supply that comes from the waste to energy transformation. In all cases, it is assumed that the community demand exceeds the output of electrical energy from the waste to energy conversion process. This modelling (and guiding principles) developed in Work Package 3 were extended in Work Package 4 and used to help identify a number of Technology Development Opportunities.

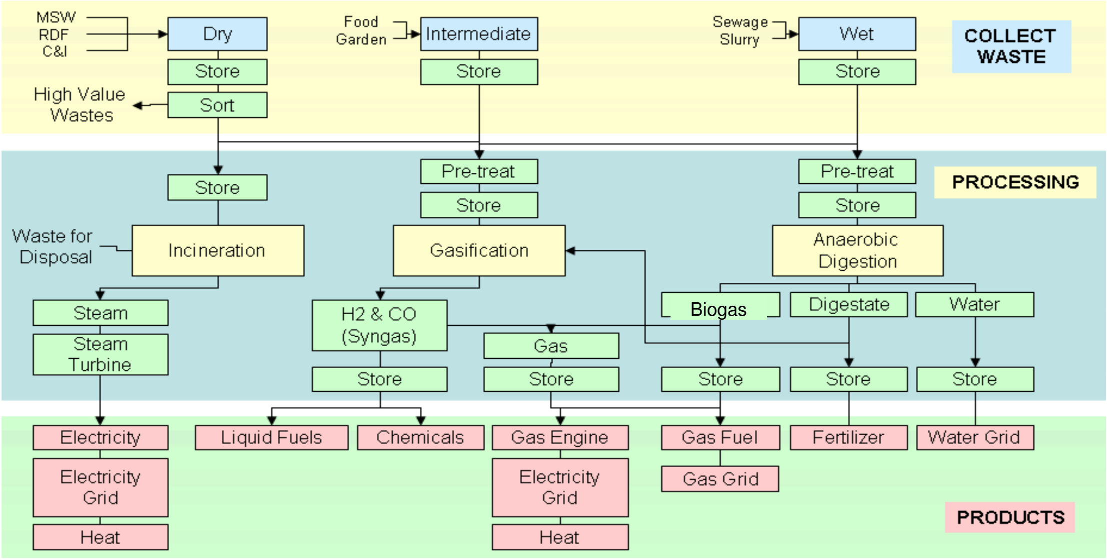

Figure 5 Schematic Technology Flow sheet developed in WP3

3 Carbon Emissions Modelling

The Work Package 4 modelling for the Benefits Case builds the Work Package 3 community scenario modelling:[17]

- Greenhouse gas emissions;
- UK scale opportunities for EfW;
- A financial returns model approach centred on the application of net present value to the industrial economic approach adopted in WP3

The model's development and operation is summarised in Appendix C to this report. The model is "dynamic", in that any assumption input values can be altered for the user to investigate their impact. For all modelling work, the emissions associated with the treatment of the residual wastes (as detailed in Table 4) has been counted only. The sorting and removal of materials from the "raw" waste streams can be carried out in a variety of manners (from householder "curbside sorting" to sophisticated machinery), and its incorporation is beyond the scope of the current project. Likewise the transportation and final use of these materials, and any energy or emissions modelling associated with these potential routes falls beyond the scope of this project.

3.1 Emissions from Waste Transport

For all calculations of the emissions from different waste processing routes for this project, the emissions associated with the transportation of the waste were included. These emissions were based on assumptions of the number of lorry miles required to transport the waste to its processing (to the energy from waste facility – "Stage 1 Miles"), and the lorry miles to dispose of any process residues ("Stage 2 Miles"). The assumed distances for each of these stages is summarised in Table 6. For the current landfill case, only the transportation emissions associated with Stage 1 were incorporated into the calculation.

	City	Town	Village	Rural
Transport Stage 1 Miles (Waste to processing)	40	40	10	10
Transport Stage 2 Miles (Waste residues to disposal)	40	40	70	70

Table 6 Assumed Waste Transportation Distances

Each lorry was assumed to have a capacity of 22 tonnes (UK standard size), and an average laden capacity of 75%. The number of lorry miles was then calculated for each waste tonnage arisings projection described in Section 2.2. Lastly, the emissions were calculated by multiplying through a value for the CO_2/mile, as taken from "Guidelines to Defra / DECC's Greenhouse Gas Conversion Factors for Company Reporting". The emissions associated with **waste transportation** varies based on the waste arisings and assumed process residuals (and hence the process efficiency, but in all cases was calculated to be **0.5% to 5% of the total emissions** from the generation of energy from waste (not including those offset from landfilling of the waste).

3.2 UK CO_2e Emissions from Alternative Waste Disposal

The generation of energy from waste generates CO_2e emissions through the

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[17] The models are available and can be re-run to cover a very wide range of scenarios and variables based on the data entered (see **Appendix C**).

combustion of the waste, or a fuel derived from it (i.e. biogas, gasifier product gas). However, waste will arise regardless of its disposal path, and its natural degradation produces large volumes of methane, which has a Green House Gas (GHG) CO_2 equivalence of 21 times[18]. In addition, the degradation of waste also produces CO_2 directly. Therefore, to accurately reflect the total emission benefit associated with energy from waste, the offset of the total CO_2e emissions would be produced from the waste needs to be taken into account.

3.2.1 Current Waste Management Practice Emissions

To calculate the emissions benefit from an increased deployment (and increased efficiency) of energy from waste technologies, the projected emissions from alternative waste management practices were calculated. For this, it was assumed that as a baseline, the current waste management practices would stay constant. As detailed in Section 2.2, the project has assessed that, at the mid case, similar volumes of waste to likely to arise in the 2030 timeframe as today. Hence, current waste and emissions data was used to verify the excel-based emissions spreadsheet model developed for this project.

To calculate the CO_2e emissions value from current practices, including landfill of waste, it was assumed that only the degradable, biogenic content of the waste degraded to produced landfill gas, and that landfill gas is formed of 56% methane (CH_4) and 31% CO_2. Currently a considerable volume of landfill gas is captured at site and used for power generation. The emissions projections from landfilling the wastes are largely dependant on the percentage of landfill gas that is captured. Currently, only ~400 of over 2000 UK landfill facilities are monitored by the Environment Agency[19]. The monitored sites typically operate at 75% capture rates. However, the rest of the sites tend to be local authority owned, and have much poorer capture rates. A UK average capture rate of 60% is often assumed, although it has been suggested that current restrictions to the Environment Agency's budget are limiting the number of inspections, and the actual capture rate is currently considerable lower than this. The official value used to calculate the UK's emission inventory is based on the monitored sites, and is currently 80%; the United Nations reports that 20% is a representative national average for western European countries. For this work, a capture rate of 75% was assumed. The captured gas volume was assumed to generate CO_2 emissions through combustion of its methane portion.

The calculated emissions from the landfilling (and landfill gas capture) of the degradable content of current waste volumes are presented in Table 7. The UK's reported emissions from waste management for 2009 were 17.9 $MTCO_2e$, of which 15.9 were attributed to landfill emissions (with the rest coming from waste water treatment (included in this project in "wet wastes") and from incineration (with energy recovery). Given the methane capture currently in place, the project model accurately reflects the emissions from current waste management practices, on the assumption that *all* waste to landfill is (eventually) degradable.

$MTCO_2e$	Volume of Biogenic (Degradable) Waste		
	0%	50%	100%
Landfill Current Wastes	0.139 (Transport Only)	8.81	17.5

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[18] Guidelines to Defra / DECC's Greenhouse Gas Conversion Factors for Company Reporting

[19] Personal communication between Phil Lonhurst (Consortium Member, Cranfield University) and Dave Brown, national technical advisor on landfill for the Environment Agency

Table 7 UK Aggregated Projected Landfill Emissions

To determine the carbon emissions benefits of generating energy from waste, the energy from waste potential projections from Figure 4 were used to calculate the associated CO_2e emissions. These emissions were then offset against other forms of power and heat generation (as represented by the projected electricity grid and natural gas heating carbon intensities), as well as against the emissions from current waste management practices. To ensure consistency between carbon emissions accounting methodologies, similar biogenic/degradable waste emissions accounting values were offset against each other – i.e. if only 50% of the total emissions from energy from waste are to be accounted for (on the assumption that the 50% associated with the biogenic portion are not counted as reportable emissions), then these emissions were offset against the current waste management practice emissions that would be generated from 50% of the waste.

3.3 Modelling Approach – Technology Scenarios

To calculate the total emissions from the deployment of energy from waste technologies, the emissions intensities of the technologies were calculated. These intensities are primarily a function of the technology system conversion efficiency. The carbon emissions model spreadsheet developed for this project cross correlated the total advanced technology based emissions with the amount of energy generated to calculate the emissions intensity for each of the technology development scenarios discussed in Section 5 of this report. The accountable emissions were calculated for the range of CO_2e emissions accounting regimes examined in this project. The calculated resultant intensities are summarised in Table 8, which includes the emissions from Transport.

CO_2e Emissions Intensity (g/kWhr)	Conversion Efficiency	% of Waste Counted as CO_2e Neutral		
		0%	50%	100%
Advanced Thermal Conversion/Treatment (Dry Waste)	15%	540	324	108
	20%	516	305	95
	30%	427	254	81
	80% (CHP)	225	144	63
	80% (Heat)	225	144	63
AD (Wet Waste)	5%	4,181	2,156	132
	10%	3,768	1,944	120
	15%	3,755	1,931	107
	20%	1,944	1,032	120
	30%	1,931	1,019	107

Table 8 Emissions Intensities of Technology Development Scenarios

As illustrated in Figure 4, the range of variables related to the assessment of the potential for energy from waste production is large and hence so are the range of emissions. For the purposes of clarity, eight representative scenarios have been selected and are summarised in Table 9. They cover a spread of technology and waste potentials.

Scenarios - all at 50% arisings accessibility				
Scenario	Conversion Efficiency		Arising Projection	
	Dry Waste	Wet Waste	Dry	Wet
1	15 %	5 %	Low	Low
2	20 %	5 %	Mid	Mid
3	20 %	20 % (CHP)	Mid	Mid
4	30 %	5 %	Mid	Low
5	30 %	20 % (CHP)	Low	High
6	80 % (CHP)	10 % (CHP)	Mid	Mid
7	80 % (CHP)	5 %	High	Low
8	80 % (Heat)	30 % (CHP)	High	High

Table 9 Emissions Modelling Scenarios

In calculating the CO_2e emissions, an important consideration is the protocol applied to the accounting of these emissions. In particular, CO_2e emissions from the degradation of waste (by any means) are commonly accounted for in one of three ways;

- All emissions are counted as being CO_2-Neutral
- Emissions from biogenic portion of waste is counted as being CO_2-Neutral
- No emissions are counted as being CO_2-Neutral

To assess these CO_2e emissions regimes, the 8 scenarios listed in Table 9 were applied in three cases:

- 0% are counted, i.e. all the emissions are assumed to be CO_2-neutral
- 50% are counted. This approximates the situation in Work Package 1 where 66% of the waste was found to be biogenic
- 100% are counted

Finally, to determine the total emissions benefit for the UK, the emissions under each of the combinations were offset against the forecasted UK electricity and heat emissions intensities under each generation scenario. The following projections and sources of the offset emissions intensities are used:

- 2015 (EDF): 494 g/kWhr
- 2015 (Committee on Climate Change, CCC) : 450 g/kWhr
- 2020 (Committee on Climate Change, CCC) : 300 g/kWhr
- 2030 (Committee on Climate Change, CCC) : 50 g/kWhr
- 2050 (Committee on Climate Change, CCC) : 10 g/kWhr
- Heat at all years: gas intensity in domestic boiler: 191g/kWhr

The combination of these variables produces total emissions projections, including offset from other sources and waste management practices, for each of the 8 scenarios detailed in Table 9. These total emissions projections are shown graphically in Figure 6, Figure 7 and Figure 8 for the accounting protocols of all waste counted as CO_2e neutral, 50% of the waste counted as CO_2e neutral and none of the waste counted as CO_2e neutral respectively. No account is made here for the additional benefit of increased electricity distribution efficiency from local facilities, generating energy close to its point of use.

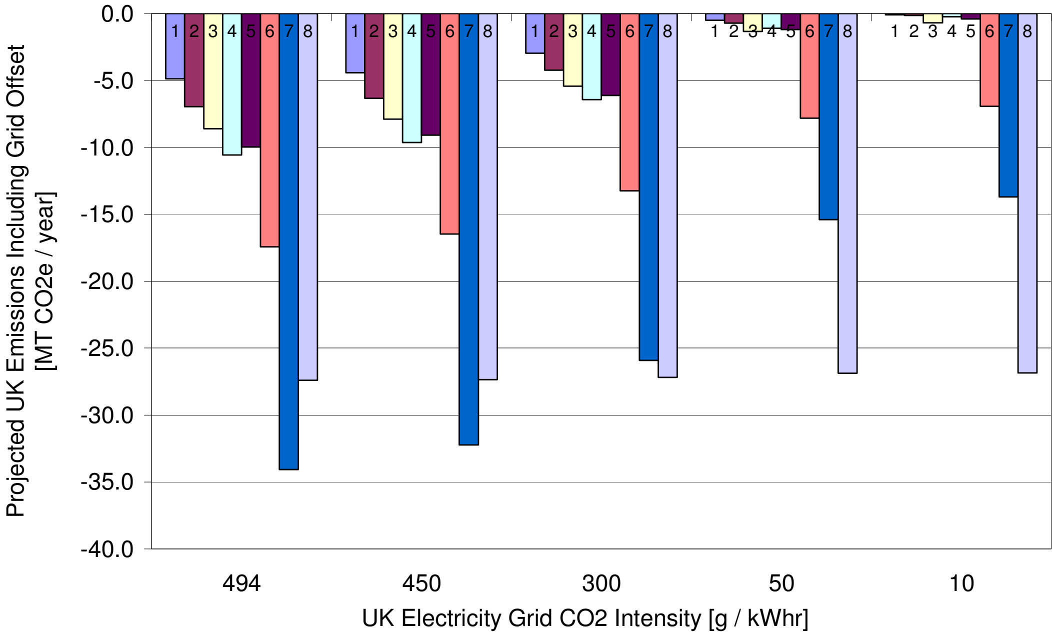

Figure 6 UK Emissions: All Waste Counted as CO_2e Neutral

The emissions benefits of using energy from waste are evident when accounting for all emissions from waste as being CO_2-neutral in Figure 6. This shows a net reduction in overall emissions, including those offset from grid electricity and gas heat sources for all technology development. At lower grid emissions intensities the offset emissions are reduced at lower energy from waste conversion efficiencies, and the offset of alternative waste management routes is also discounted (as these emissions are also counted as being CO_2e neutral). Hence the benefit in this case is derived from **offsetting other sources of electricity and heat generation**.

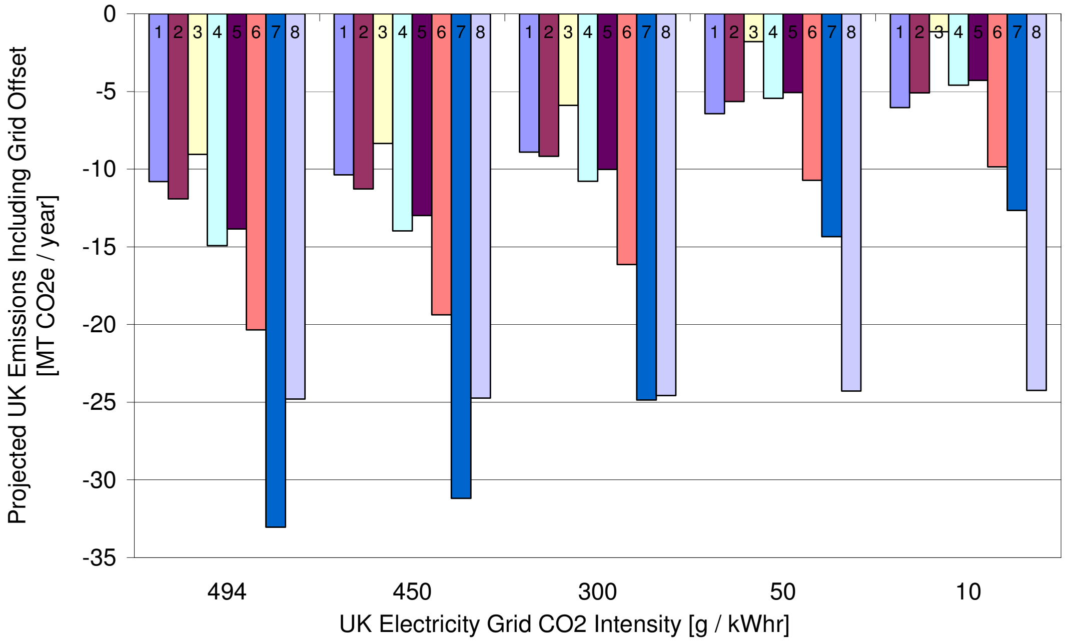

Figure 7 UK Emissions: 50% of Waste Counted as CO_2e Neutral

The projection of CO_2e emissions from the number of potential waste arisings and conversion efficiency scenarios assessed in Figure 7 is most representative of the current condition where emissions from the biogenic fraction of the waste are discounted. In this case, all of the scenarios show an emission reduction, with a UK reduction of 15 MTCO$_2$e/year being projected to be achievable with modest technology conversion efficiency. This benefit is largely driven by **offsetting CO$_2$e emissions from the landfilling of the biogenic portion of waste** (methane production form degradation), and from offsetting grid based electrical generation. Figure 7 also shows the benefit from using the “waste” heat in CHP facilities, as denoted by Scenario 6, and again reiterates the importance of facilities at scales where the heat can be used effectively.

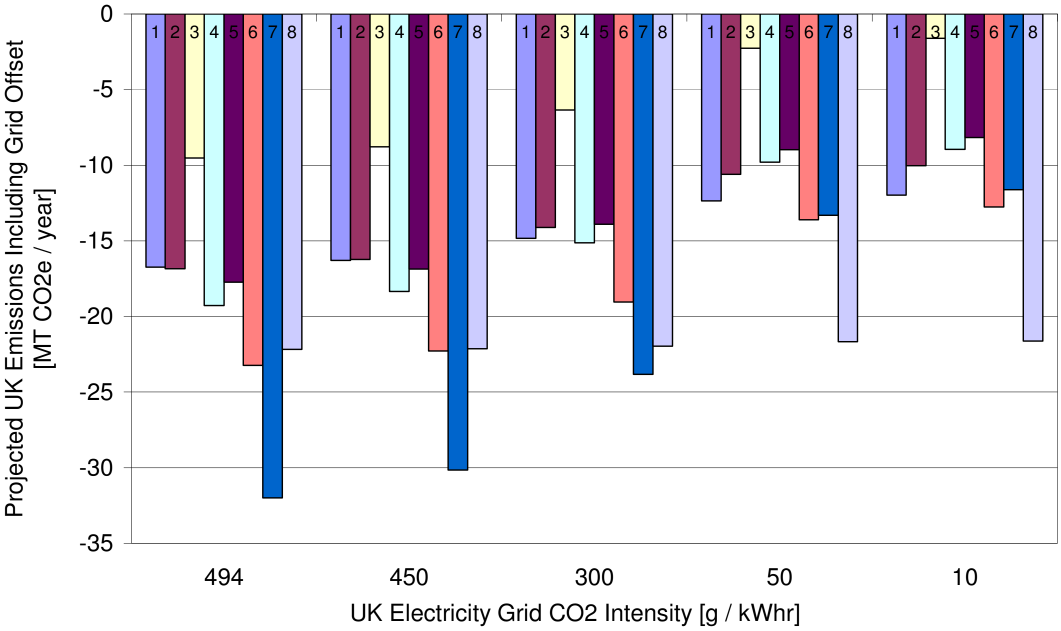

Figure 8 UK Emissions: No Waste Counted as CO$_2$e Neutral

If the emissions from all wastes are counted (in terms of CO$_2$e) from both the energy from waste technologies and from the alternative waste management practices, as illustrated in Figure 8, emissions reductions of around 12 MTCO$_2$e/year are projected to occur in the 2030 timeframe for most technology and waste scenarios. In this case the benefit comes mainly from **offsetting all the methane production from landfill** by conversion combustion to produce CO$_2$, with the power (and heat) produced through that combustion offsetting other forms of energy generation.

Overall, for each of the technology and waste arisings scenarios, the deployment of advanced energy from waste technologies is projected to contribute to a **net decrease in UK CO$_2$e emissions of between ~5 and ~10 MTCO$_2$e/year** in 2030 at mid-point technology conversion and waste arisings scenarios. **Greater emissions reductions are associated with high total conversion efficiency technologies, both to electricity and from utilising heat.**

4 Financial Returns and Variables

4.1 Scale of EfW Development Opportunity

WP3.3 assessed technology development options under a number of community scenarios. The scenarios were: a city for 500k people, a town of 50k people, a village of 5k people and a rural community of 500 people. These community scenarios are referred to throughout the report. It was concluded that if the total volume of wastes arising in the UK are divided by the number of communities at each scenario scale, the number of opportunities for EfW plants can be identified. Table 10 shows that the UK could support 76 plants handling 500kt/yr, 950 handing 50kt/yr, and over 9,000 plants handling less than 5kt/yr.

City	Town	Village	Rural
500kt/yr	50kt/yr	5kt/yr	500t/yr
76	946	4,544	4,544

Table 10 Number of UK plants for each community scale

The current UK market is skewed towards larger scale plants handling over 200 kTpa, and the data here indicate that the UK is only likely to be able to support 150 to 200 of these plants using existing well-established technology. Currently there are over 40 plants of this size in planning. In contrast, there is an unaddressed market for around 10,000 units of smaller scale plants. Therefore, there is an opportunity to develop plant designs and supply chains for thermal plants operating at 50 kTpa or below as there is little evidence for operating or economic plants at this scale.

4.2 Techno-Economic Evaluation of Technology

The calculated emissions reductions from the generation of energy from waste are predicated using conversion technology operating at realistic current efficiencies without heat use. To define the required technology development steps to reach these (feasible) efficiencies, an assessment was carried out into the current state of energy from waste technologies.

Wastes classed as wet (>80% moisture) and having high biogenic content are particularly suitable for the generation of gases in anaerobic digestion plants. Dry wastes (<20% moisture) are best suited to thermal processes such as incineration, gasification or pyrolysis. With incineration, energy can be recovered using a steam cycle with a total system electrical efficiency, to up to about 22%. Gasification and pyrolysis (advanced thermal processes) produce a mixture of carbon monoxide and hydrogen known as syngas. This can be burned in a boiler to recover energy via a steam cycle (fuel gas to power efficiency around 20% below ~10MWe[20]), or potentially in a gas engine or turbine (fuel gas to power efficiency ~25 – 40% at all scales), or other gas-fuelled power generator. It can also be used for the production of higher value products such as liquid fuels or chemicals depending on the conversion technology. Total conversion efficiencies are strongly dependant on the efficiency of the gas use, making the use of gas engines and turbines particularly attractive at the power generation scales under consideration in this project. The system outline above is shown diagrammatically in Figure 5. This systems have been modelled in detail and the systems models developed for WP 4 show typical scenarios, but also have the flexibility to be used to model a wide range of potential

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[20] World Alliance for Decentralised Energy (WADE); http://www.localpower.org/deb_tech_st.html

integrated waste processing systems for various communities and technologies.

For each of the potential technology options, the cost of energy generation, and commercial viability, is dependant on a number of “controllable” and “uncontrollable” variables. Controllable variables are directly related to the technology, while uncontrollable variables are partially or entirely influenced by variables outside the control of the technology. The controllable and uncontrollable variables, which impact the technology economics, are summarised in Table 11. The uncontrollable variable of the cost of capital is linked to the technology itself by its bankability, which is normally based on its level of development and track record. However it is also linked to the overall availability and cost of capital in the market well-proven technology attracts a lower cost of capital.

Variable	Controllable/ Uncontrollable	Effect on Profitability	Comments
Capital Cost	Controllable	Lower capital decreases cost of energy	Need to guard against loss of function as capital reduced
Operational Cost	Controllable	Lower operational cost decreases cost of energy	Can be proportionally high for smaller plants
Conversion Efficiency	Controllable	High conversion to high value products increases profitability	All outputs should be viewed as value creating and processes should be developed accordingly
Feedstock Cost	Uncontrollable	Higher price lowers profitability	Set by a combination of legislation and market conditions
Cost of Capital	Uncontrollable	Lower cost of capital increases profitability	Set by macro economic conditions and technology risk

Table 11 Variables Impacting Technology Economic Performance

An assessment of the economic performance of the energy from waste technologies has been carried out by assessing the net present value (NPV) of the systems in relation to a range of variables, as detailed in Table 12. Plots have been produced that show the relationship between capital cost and process conversion efficiency. On each of these graphs a line has been plotted to show NPV = 0. Plots have been prepared showing the base case and its sensitivity to the variables listed in Table 10. A plot is shown for each of the major energy from waste technologies. Points above the NPV=0 line are uneconomic and will never deliver acceptable returns while points below the line have a positive NPV and are potentially investable propositions. The aim of all the technology development options is to ensure that the technologies are below the NPV=0 line and as such can attract investment finance.

	Base Case	Low Projection	High Projection
Cost of Capital	10.0 %	7 %	16 %
Product Revenue	£0.05 /kWhr	- 40 %	+ 60 %
Feedstock Cost	£45 /tonne (dry) £10 /tonne (wet)	-20 %	+ 20%

Table 12 Net Present Value Anaysis Factors

WP 3.3 also identified a set of technology improvement drivers that informed the selection of variables for the NPV analysis. These are to:

- Reduce the capital cost per unit of investment. This could be through the economies that come from large-scale plants or through long production runs of similar units leading to economies from repetition. It should be noted that currently all plants require some support mechanism through either the landfill tax at the supply end or the feed in tariff (FIT) or renewable obligations certificate (ROC) system to be economically viable. A capital cost reduction of over 30%/tonne of feed would be required to remove the need for public sector support mechanisms;
- Improve the yield of higher value products and making use of all by-product streams would be of great value. The technology study and experimental work indicates that all technologies studied have low conversion efficiencies for the transformation of feedstock into energy. In many cases the usable energy yield is up to 50% lower than conventional fossil fuel alternatives[21];
- Increase the efficiency of energy conversion both electrically and thermally. Pure thermal systems that convert gas into heat for local use can reach conversion efficiencies as high as 85%. This requires a different approach to gas use either in grid or in local heat networks;
- Handle variable feedstock form and moisture content. This is essential to the successful operation of waste to energy plants. The evidence from the work to date also indicates that mixed wastes have similar elemental composition, but differ widely in form and moisture content;
- Produce homogenised feedstocks through mechanical, biological or thermal pre-treatment;
- Meet legislative and regulatory requirements for safe and beneficial operation;
- Be robust, flexible, reliable and are easy to operate.

4.3 Incineration

The incineration (with energy recovery) of wastes is widely practiced and largely technically proven, within the limitations outlined above. Based on this state of the technology, there are many case studies available, although exact cost and operational performance information remains commercially sensitive. Based on the best available data from a variety of sources[22], the current state of the technology regarding conversion efficiency and capital cost is shown in Figure 9.

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[21] i.e. total efficiency from waste feedstock to usable energy. For this project, the scope is the direct generation of heat and electrical energy. The production of fuels and chemicals will be examined in a separate piece of work; whilst these may be produced efficiently from the technologies under consideration, a total assessment should include the efficiency of their use to usable energy to enable a direct comparison to other energy forms.

[22] Provided in confidence by Sita at Haverton Hall, 14th September 2010

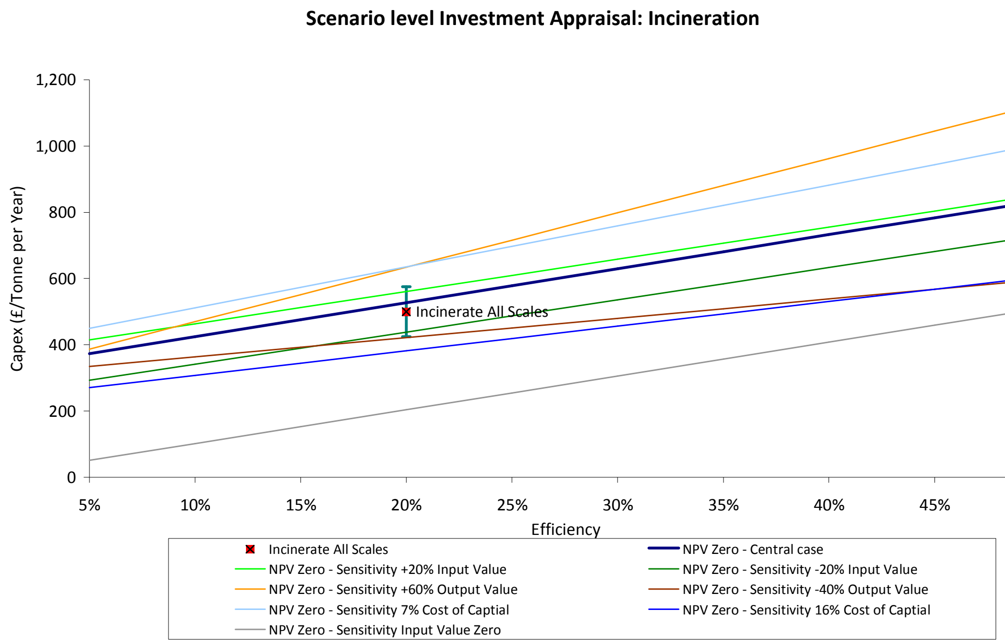

Figure 9 Capital cost vs. Efficiency (Incineration)

Figure 9 shows that the economics of these plants is currently marginal and returns are driven by regulatory and fiscal incentives. Most particularly avoiding landfill tax and meeting the LATS legislation coupled with ROCs. An increase in the cost of capital or a decrease in input or output value would generate negative net present values (i.e. point falls above the NPV = 0 line). This is also borne out by the fact that incineration plants require long term, minimum value (index linked) feedstock contracts and off-take to attract local authority backed (low interest) finance.

Work Package 2 identified that electrical conversion efficiency could be increased to a theoretical maximum of around 35% through the advanced thermal conversion (gasification or pyrolysis to produce a gas) of dry wastes, and the subsequent use of the gas in combined cycle gas engines, turbines or potentially fuel cells. Systems comprising of these technologies are also typically modular, and hence scalable between the community scales previously identified. In assessing the current status of such technologies integrated plants and processes should be considered. Such systems comprise pre-treatment, conversion and post-treatment steps as well as heat and power generation. In many cases each process step has been developed in isolation and fitted into existing operating chains. In general this has not worked and the development of high efficiency, local scale energy from waste systems has had little technical success in the UK.

A technology landscape assessment commissioned for this project from gasification and pyrolysis specialist consultancy CARE (Conversion and Resource Evaluation Ltd) highlighted 19 UK development and pilot plant activities, although none appear to be currently fully operational. The majority of the work on the advanced thermal treatment of waste has been applied to well defined biomass fuels and the evidence suggests that there are few, if any, viable systems operating even on biomass. A notable exception is the Japanese waste management industry, where high disposal costs have focussed directed the industry towards very high temperature gasification (using plasma), although energy recovery rates are low (~5 %) and plant capital costs are exceptionally high[23].

In assessing why these technologies have not yet been economically developed, it appears that most demonstration facilities have combined a number of component technologies, each having been developed in isolation. The lack of integration and system design means the developments have been unsuccessful. An example of this approach is the ARBRE project, which suffered a number of technical issues in commissioning, which in association with varying financial circumstances could not be economically resolved at the full plant scale. Whilst the initial capital cost may be broadly comparable to other thermal plants (although precise economic data has been found to be extremely difficult to come by), operational difficulties have driven costs above the NPV=0 line where the plants are not economic. This is shown in Figure 10. These data are based primarily on that provided by the CARE and AEA reports commissioned for this project. However, the actual points plotted are only indicative.

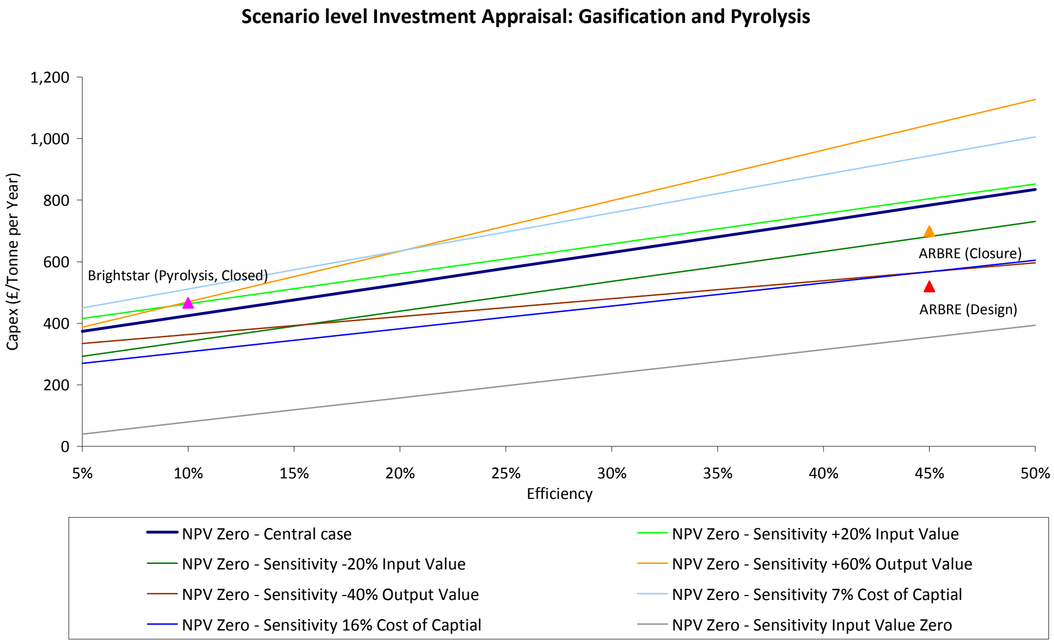

Figure 10 Capital cost vs. Efficiency (gasification and pyrolysis)

Opportunities and requirements for development to enable the successful operation of thermal technologies are discussed in Section 5.1.1 of this report.

For the treatment of wet wastes, anaerobic digestion has been used in the sewage treatment industry for many years. The application of this technology to other wet wastes, including agricultural slurries and other food wastes is gaining acceptance in the UK. This is mainly due to the introduction of incentives for electricity produced from AD combined with changes to the classification of wastes that can be put to land. The use of agricultural and waste driven AD plants is common in much of Europe e.g. Germany and Denmark have over 3000 plants. The analysis of UK opportunities for this project showed that overall energy conversions are typically very low with overall electrical system efficiencies in the range of 5%-10%. Their current status of cost and performance, as taken from case studies contained within the AEA technology landscape report also commissioned by this project, is

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[23] AEA Technology Landscape Report

shown in Figure 11. This figure shows that current capital costs at higher efficiencies are too high to be economically viable (this analysis does not take incentives such as Renewable Obligation Certificates (ROCs) into account).

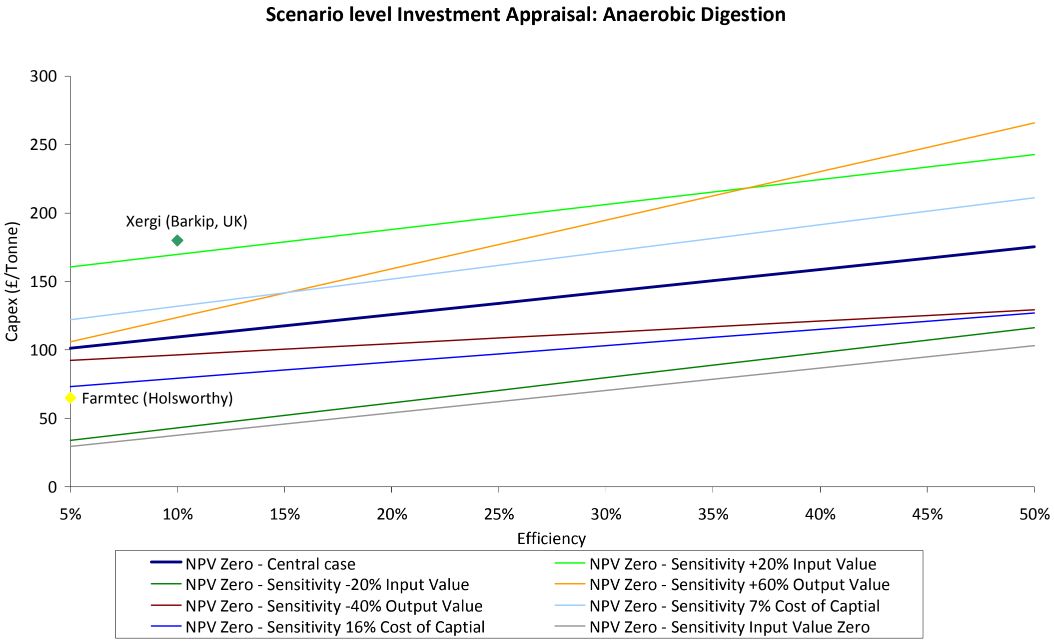

Figure 11 Capital cost vs. Efficiency (AD)

Fundamentally there is a need to reduce capital cost and increase efficiency of conversion of feed into energy for all the main energy from waste technologies. This aim and ways of promoting its delivery are the theme of the following sections in this report.

5 Technology Development Opportunities

The previous sections of this report have identified the potential emissions benefits that may be enabled through the deployment of energy from waste, and the costs (capital and operational) that technology systems are likely to be required to meet to enable their commercial deployment and hence for the emissions benefits to be achieved in practice. In particular, these analyses showed that the conversion efficiency of the useful energy from the raw waste stream(s) has the highest impact on both the emissions output, and the acceptable cost parameters.

The open literature and technology landscape reports commissioned for this project from AEA and CARE provide an array of information regarding the current operational efficiency and cost data of technologies which have been deployed (commercially or in demonstration plants), or are in development. Due to the number of organisations involved in the operation, construction, development and financing of advanced energy from waste systems, and the competitive nature of this industry, definitive data regarding operational experience and costs can be difficult to come by. However, the data and surrounding anecdotes are coherent in that they suggest that the core advanced thermal and biological conversion technologies are not sufficiently well developed to enable their commercial deployment.

Accordingly, in conjunction with the test and modelling work carried out in this project (Work Packages 2 and 3 respectively), a number of technology development opportunities have been identified which would advance the technology systems towards their commercial deployment. In addition to these core technology development opportunities, a number of adjacent areas for development have also been identified, which fall outside the scope of this project, which would add further value and benefit to the development of the core technologies described below. As such these additional development opportunities are dependant on the success of the primary development opportunities.

At the highest level, the technology failings to date as detailed in the Care and AEA technology landscape reports are felt to be due to poor equipment definition, manufacture, integration construction and operation. The primary technology development opportunities have been selected as they are felt to require a coordinated and professional approach that the ETI could bring.

5.1 Primary Technology Development Opportunities

The primary technology development opportunities identified in this project, from the test and modelling work and verified with stakeholder workshops, relate to the core technologies associated with advanced thermal and biological technologies at scales of 50 kTpa or below (approximately equating to 5 MW or below).

5.1.1 Advanced Thermal Processes

Currently, high efficiency thermal technology systems are largely un-proven, which has led to the identification of two primary, interrelated, areas of focus requiring development. Both areas of focus relate to advanced thermal processes producing a gas for subsequent high efficiency heat and power generation. The first of these is a high-level system development to lower the capital cost (per tonne/year processed) and increasing the conversion efficiency. Due to the highly interactive nature of the technologies comprising an energy from waste system, such development would need to be carried out holistically, taking into account every aspect from waste pre-treatment to useful energy conversion, including the thermal reactor and gas cleaning steps. The latter of these form the second primary development opportunity; the cleaning of thermally derived gases (from gasification or pyrolysis) to a quality sufficient for downstream use in efficient conversion devices (engine, turbine, catalytic conversion, etc.). Gas treatment has repeatedly been shown to be the most technically challenging aspect of an advanced thermal energy from waste system.

5.1.1.1 Gasification System (0.5 – 5 MW) System Development

The gasification of waste materials in fluidised bed or downdraft gasifiers has been identified as a significant development opportunity as there are currently few processes that work using mixed feedstocks at feed rates of 50kt/yr or less. This has also been demonstrated by the scale and operations of pilot plants assessed as part of this project (see Appendices B and D). Technology to date has been developed for consistent feedstock properties (biomass etc). To date such systems have also not been co-developed with feedstock preparation, pre-processing/blending and handling systems to help reduce gas cleaning demands and other downstream issues. A further benefit of this scale of technology relates to planning and siting applications, which typically face fewer oppositional issues at smaller scales. This is particularly the case when the surrounding community is the direct beneficiary from reduced waste handling impacts (cost, lorry movements etc.), and from low cost heat provision.

In the development of these systems, it should be considered that the operation of the component technologies is inextricably linked to systems operation. As such, pre-treatment, reactor design, gas cleaning and end-use should all be considered simultaneously as part of a linked and integrated system. Indeed, it would appear (e.g. from AEA and Care (Appendices B and C reports) that the lack of integration during the technology development phase has to date been the cause of most operational issues. Poor design is a clear issue as is testing before installation in many UK demonstration plants. Upstream and downstream processing are as important (and costly) as the core reactors, as it is considered that a lack of such appreciation to date has led to several poorly designed systems. In addition, the UK ROCs legislation rewards only carbon-neutral power generation; this leads to development of grid-electrically heated reactors with very low (possibly negative) overall system efficiency. The use of SRF as a semi-defined pre-treated fuel has to date not been fully exploited, as there is currently an over production of this waste derived fuel in the UK. However, the suitability of use of this feedstock would depend on the system level investigation, cost and optimisation, including the final gas use in gas engines and/or turbines.

Technologies should be developed to support communities generating waste and mixed feedstocks with the aim of developing innovative gasification solutions that reduce capital cost and increase operability of small-scale units. Units could be single stream or multiple installations of modular units with lower throughputs. In addition to operating on waste feedstock, the plant could be designed to convert locally sourced coppice, grass and other biomass sources. Developments are likely to incorporate thermal process improvement through the use of alternative oxidants (H_2O, O_2 or CO_2), and optimised process parameters to maximise carbon conversion/gas CV, while reducing/controlling gas contaminant production. While steam should be readily available within most plants, the addition of other oxidant gases such as O_2 and CO_2 would need additional process steps. Although air enrichment (for higher O_2 concentrations) may be achieved at relatively low cost, the production of pure O_2 would require the development of small scale, low cost air separation units which would be an enabling technology development in its own right. For CO_2 capture and potential sequestration, one option would be to separate CO_2 from the syngas using membranes or solvents/sorbents, thus simultaneously boosting the syngas CV. Furthermore, there are benefits from an increase in conversion efficiency through improved reactor design to aid heat transfer. Where high levels of tars are produced, their cracking to improve overall gas production or their recycling either into the main reactor (for degrading) or to supplement the fuel being used to provide process heat represent significant opportunities for improvements in process efficiency. In this case, there is a link between the feedstock materials and the scale and complexity of the gas cleaning required. Controlling feed mixes through blending provides one element of an integrated approach to reducing the costs of gas cleaning. To achieve this, developments are required in feedstock monitoring and waste fuel standards.

A major risk of the use of these technologies is how the physical form of the waste affects the operation and stability of the overall process. Specifically, the feeding of material to the reactor and the thermochemical reactions are the most affected, although there are a number of feeding systems tailored for the specific material being transported. Therefore, to enable more reliable and robust technology operation, emphasis should be placed on the pre-treatment of the feedstock to ensure that operational issues are not encountered. This can take the form of moisture control and or physical form homogenisation (e.g. pelletisation), although further work to understand the cost, system efficiency and benefit trade-off would be required through directed experimentation. In addition, work will be required to ensure that processes can meet the requirements of the legislative and regulatory system.[24]

The core gasification reaction offers flexibility with differing feedstocks (within defined moisture content limits), and the time taken to adapt to another fuel source in a well-designed gasification plant could be minimized. Small plants at the town and village scale with appropriate instrumentation and control may offer further flexibility in meeting demand profiles through the incorporation of gas storage, either pre- or post- gas cleaning as appropriate as the gasifier itself will not be able to load-follow due its thermal inertia, and the requirement to process the continuously arising waste. The incorporation of load-following abilities through gas storage would allow the sale of generated power at higher values, and disassociates the load following operation of the gas engine with the required constant operation of the gasifier (due its inherent thermal stability, and constant supply of non-storable waste feedstock). Gasification produces a product gas (similar to syn-gas). Syn gas comprises H_2 and CO, which is widely usable in a range of downstream processes. Product gas often has high concentrations of H_2 and CO and if it could be used in syn gas markets it could offer flexibility to the application of the technology in producing high value outputs from waste feedstocks.

For example, the controlled use of feedstock blending can be used to optimise performance and constrain emitted contaminants to within downstream equipment tolerance and environmental emissions limits, as well as providing operational stability and performance benefits. Such a suggestion is difficult to ascertain without practical experimentation but the evidence here points to different mixtures

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[24] See AEA report in **Appendix B** as part of WP2.

of materials likely to result in different gas outcomes. In addition, the ability to assess feedstocks through the development of nomographs for different waste material mixtures based on their chemical and physical properties could be of value in the assessment and optimisation of feedstock mixes or blends coming into a facility.

Feedstock feeding issues were experienced with certain waste mixtures due to “sticktion” and jamming, caused by moisture content and material thermal decomposition effects. However, the feed systems used on the rigs were not optimised for the material mixtures tested and in practice the feed system may be appropriately designed. However, deviations from the design-for feedstock may present issues in this regard, and increased system robustness might be achieved through feedstock manipulation. Standardisation in feedstock properties, such as the production of RDF (Refuse Derived Fuel) or SRF (Solid Recovered Fuel), or other physical homogenisation techniques such as pelletisation would be expected to help in this regard, although may instigate a significant energy penalty, and so would need to be balanced in terms of total system efficiency. Additionally, these processes requirements are likely to increase the feedstock cost.

The quantity of output gas was measured to be approximately constant for all material mixtures for each technology. However, the gas composition, including the levels of trace constituents, was found to vary depending on the feedstock composition. For the gasification tests, variable levels of tars and other contaminant compounds and elements were measured. Whilst gas engine operation was successfully shown on simulated, clean gasification type gases, these contaminants would be expected to adversely affect engine operation. These contaminants typically cause blockages and constrictions, and/or corrosive damage. In either regard, the end effect is to cause an increase in the cost of energy generated as engine performance (and hence amount of heat and power generated) is reduced, and the costs associated with maintaining engine performance are increased. The requirement of adequate quality gas in efficient downstream generation technologies such as gas engines and turbines reiterates the paramount importance of cost effective, robust gas cleaning technology to enable effective utilisation of the waste material resources.

5.1.1.1.1 Current TRL Assessment

The Technology Readiness Level (TRL) of any system of component technologies, especially a system of technologies under development, is difficult to assess due to the range of component TRLs combined with the inherent TRL of integrating these into a system.

The range of suppliers of core gasification reactors at all scales, and the relative simplicity of the core technology leads to assessment that small scale gasification, as a whole, is currently at a TRL of ~5. However, the use of mixed waste materials poses a challenge for some reactor types due to the variety of physical forms and thermochemical behaviours of the materials present in such a mixed stream. In this regard, fluidized bed gasifiers are more suited to the processing of mixed wastes, although downdraft gasifiers are more suitable for smaller scales (<~5 kTpa per unit), though may require more waste pre-treatment. The use of mixed wastes in downdraft gasifiers may be estimated to be a slightly lower TRL of ~4. In contrast, the large-scale gasification of very homogeneous materials (e.g. pulverised coal) is widely practiced (e.g. South Africa) and may be deemed to be at TRL 9.

At a system level, integration of component technologies at a range of individual TRLs poses a considerable challenge, and does not act to increase the system TRL. This interaction usually means that system level operation is at the TRL of the least developed component. Despite the large number of organisations involved in this industry at a global level, and the number of development, demonstration and pilot plants as detailed in the technology landscape reports commissioned by this project, the lack of robustly operating high conversion efficiency plants suggests that this integration aspect should not be underestimated. The industry status regarding integration of the pre-treatment and core reactors with gas cleaning technologies (range of TRLs, as below) and special gas engines, turbines or other processing technology (TRL ~2 to ~4) leads to an overall gasification and engine based energy from waste system level TRL assessment of ~3.

5.1.1.1.2 Prospective Technology Development Process

It is the view of the consortium delivering this project that the selection of specific technology types or suppliers (often linked) would not be appropriate to enable the ETI to commission a specific closely defined and bounded technology development project towards the deployment of highly efficient and cost effective gasification based energy from waste systems. Instead, it is felt to be of higher value to recommend a development methodology and process, with the intention that this would enable the most suitable technology and skills providers to respond to such a process call.

To provide some guidance, a development process is provided below. Due to differences in gasification reactor type suitability to different scales (and the associated system level interactions), such a process would be required to be targeted at a particular scale, where alignment with the City, Town, Village and/or Rural scales is recommended.

In all cases, the fundamental industry requirements for the successful development of gasification based energy from waste systems are a facility that allows the development and proving of gasification and cleaning processes and funding for gasification and cleaning process development projects. To enable commercial deployment, technology development must be directly scalable to commercial facilities, and as such should be carried out at approximately 1 MWe, where both downdraft and fluidised bed gasification may be applied. This relates to an approximate waste feedstock rate of 10 kTpa. For the selected scale(s)/base technology(ies), the following project steps are recommended:

1. Investigation of specific gasification reactor design requirements for mixed wastes and linkage to up- and down-stream processing requirements with initial investigation at pilot scale where appropriate
    a. Review existing projects utilising mixed wastes as a feedstock to identify design limitations and best practice as appropriate.
    b. Experimental analysis using range of segregated and mixed wastes, full measurement of input and output parameters; interaction with material pre-processing and feed system
    c. Build detailed computer models of reactor for process development and optimisation
    d. Initial development of reactor design to understand influence on material processing requirements, process stability, controllability and output parameters (gas quality)
    e. Examination of effect of use of alternative/mixed oxidants
    f. Consideration of process residues (including from gas cleaning) –

their potential value, re-insertion to the process or disposal in an environmentally and cost effective manner.

2. Upstream feedstock processing and blending
    a. Experimental work and practical trials to show the effect of feedstock type, moisture content and blending on reactor performance
    b. The development of processing technology to handle wide ranges of feedstocks in a way that makes them compatible with the downstream processes
    c. This could form a sub-project in its own right
3. Parallel investigation into down-stream utilisation gas quality requirements
    a. Experimental parametric study of effect of varying gas quality (composition, contaminants (gaseous, particulates and tars) on performance (robustness, time-degradation) of high efficiency gas engine and turbine energy generator(s)
    b. Could be carried out on "simulated" clean gases (from known source) or varying compositions doped with contaminants, or using output gas from 1., or other waste gasification gas source
4. Gas cleaning requirement and technology investigation
    a. Combined evaluation of output from 1. and 2. to examine gas cleaning requirement and trade-off on system performance
    b. Detailed below, as can be project in its own right
5. Process integration and system optimisation engineering
    a. System construction including gas cleaning
    b. System process and control development (key robustness aspect and development opportunity)
6. System Validation and Demonstration
    a. Estimated Developed Technology Status ~TRL 5-6

The UK has a small number of facilities that could support this development programme which are outlined later in this section. It is proposed that the ETI programmes seek to build on this existing investment to create a strong national facility rather than a number of smaller similar facilities. The facility should leverage existing component technologies in each of the process steps (pre-processing to power generation). Technology development projects are likely to be based on each of the component technologies, centred around the core gasification technology. To enable the facility to be as versatile as possible, the gasifier could be multi-configurable, or separate fluidised bed and downdraft gasifiers with a "plug and play" approach to enable equipment to be easily interchanged. Technology suppliers are likely to be dependant on specific project call respondents, in turn dependant on the specific development aim. In this regard an initial system development call would provide equipment in each of the process stages, prior to subsequent component and system optimisation.

The steps outlined above have timelines and budget requirements as below, estimated by the consortium from previous research and development activities at a similar scale:

- Equipment capital: £10M to £15M
    - Pre-treatment: £1M - £2M
    - Conversion: £2M - £3M
    - Gas-Cleaning: £3M - £4M
    - Power Generation: £1M - £2M
    - Control System: £ 1M - £2M
    - Waste reception, gas storage and instrumentation etc. £1M - £2M
    - Construction: ~£1M

- Initial investigation materials and services: £5M
- System optimisation materials and services £5M
- Additional management and administration costs
- Total ~ £20M - £25M

- Technology procurement and commissioning: 1 year
- Initial testing and development: 2 years
- Optimisation and validation: 2 years
- Total ~ 5years

The potential for further development and acceleration is felt to be relatively high, with a consortium estimated timescale for development to TRL 9 of 10 years at an estimated cost of £50m to £100m for initial scoping of project to demonstrated technology robustness.

Based on the above integrated system development programme, and the current state of gasification system technologies (and analogous systems), the consortium estimates that operational systems may be produced at the costs and conversion efficiencies as summarised in Table 13. This range of values has been used to project the potential cost of energy, as detailed in Section 6 of this report. In all cases, these values are projected as robust, operational gasification based energy from waste systems at the scale considered (1-10MWe) are currently not available due to technical limitations.

		Low	Middle	High
Capital Cost [£/tpa]	Electricity	350	500	650
	Heat	100		
Operational Cost [£/kWhr]	Electricity	0.02	0.05	0.1
	Heat	0.01		
Conversion Efficiency [%]	Electrical and Heat	30%	38%, 50%	80%
	Waste Feedstock Mass Conversion	50%	65%, 80&	100%

Table 13 Gasification System Level Performance Targets

When considering likely costs of technology systems, their scale has a considerable bearing. For the costs outlined in Table 13 the higher costs (in terms of per tonne per annum) should be associated with smaller scale systems, and lower costs with larger systems in the range of 1 to 10 MWe under consideration in this project. The costs projected in Table 13 broadly align to those from other sources,[25] though are slightly higher than some estimations to compensate for the additional technical complexity fully operational systems are likely to require. To account for the range of uncertainty of costs which would be associated with higher TRL systems than those currently existing, the range of capital and operational costs may be assumed to cover technology systems of any scales over the relevant range (with the implicit coarse assumption that economies of scale do not occur over this range). Lastly, the linkage of capital and operational costs to conversion efficiency has purposefully not been made in this project, as the current state (TRL) of technology systems (for waste or biomass) is not well enough developed to enable any meaningful correlation between these parameters to be established. The values presented in Table 13 cover the range that are deemed to be achievable of each metric, following a comprehensive technology development project as outlined below.

5.1.1.1.3 Concurrent Development Activities

Any system development activities undertaken by the ETI should build on the extensive component development which has taken place in the gasification energy from waste industry to date. In reports commissioned for this project, CARE identified 19 recent UK active gasification companies, with one or more recent UK projects (development and demonstration), including detailed account of technology status reached. Additionally, AEA identified 160 global companies actively working in developing gasification technologies. Combined with those companies developing pre-treatment (sorting/shredding) technologies, global activity across the technology chain is extensive. However, despite this level of involvement, system level integration appears limited, with the result that few plants with advanced (engine/turbine etc.) gas utilisation are commercially operational, with several high profile biomass projects having failed (e.g. ARBRE, Bioflame, Waste-to-Energy Ltd) due to these reasons.

The greatest development in waste gasification has probably taken place in Japan. However, Japanese incentives reward waste destruction with minimal emissions

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[25] e.g. as supplied to the project by the ETI's technology stakeholders on the 14th of June 2011, when normalised to 8,000 hours per year operation.

over energy recovery, and hence tend towards high temperature gasification processes (~1600C). This results in levels of low gas contamination, but also a low calorific value of the gas and high parasitic loads. This, usually combined with a steam boiler, results in overall recovery efficiencies of ~5 to 15%, considerably lower than current best incineration based plants, and at a considerably higher cost. Switzerland based Thermoselect are a major supplier to the larger gasification energy from waste market, including allegedly with engine operation. However, system costs are reported to be "high", with a system efficiency of around ~15%. Plasma gasification is also used to achieve required temperatures, at very high capital costs (~£26M/MW – Juniper Review of AlterNRG/Westinghouse plasma gasification process for MSW compared to ~£5M/MW typical of UK incineration based systems). Given these high costs and low conversion efficiencies, as well as the larger scale of these plants than those identified relevant to the community scenarios for this work, suggest only limited technology applicability to any further ETI system development projects.

A number of development activities are ongoing in Europe, India, America and elsewhere on small scale biomass gasification. However, the lack of deployment of these technologies suggests that further development is required to enable their successful operation on a combination of biomass and waste feedstocks.

A number of UK universities have relevant waste processing and thermal treatment capabilities. For example, Cranfield has a range of thermal process rigs at 50-350KWth scale (updraft, downdraft, fluidised bed and circulating fluidised bed rigs) with fuel preparation and gas cleaning facilities, as well as a range anaerobic digestion units, combustion engines and burner rigs for gas combustion trials; these facilities are fully instrumented and in most cases have been benchmarked against industrial scale equivalent plants. Additional UK academic facilities exist at the Universities of Newcastle (downdraft gasification), Aston (flash and intermediate pyrolysis) and Sheffield (gasification + fuel analysis lab). Industrial facilities are more difficult to ascertain, although CPI has a 1.8m diameter and 3m high gasifier in construction with flexibility to do updraft, downdraft, fluidised bed and blast furnace gasification, which has all required utility and emissions permits as it is a collaboration with Tata Steel on an existing site with operating permits and utilities in place. This facility has a deliberately built hard standing to test other technologies with the clean-up train or as pre to post treatment facility to the core gasifier, and the facility could be further expanded for little additional cost. CPI are also building an 850kg moving wall batch pyrolysis unit on the same site to treat coal and waste. This will include analytical and modelling (CFD etc) capability. At Wilton CPI has a small fluidised bed set-up for depolymerisation and a small stand alone gasifier.

5.1.1.1.4 Technology Development Risks

The development of small scale waste gasification technologies is regarded as being medium risk. The large number of organisations involved in biomass gasification shows the extent of development occurring in this area, much of which is applicable to the use of mixed wastes as a feedstock. However, the number of organisations developing gasification systems, combined with the long history of development and lack of commercially viable systems also indicates that there are significant technical challenges. It is thought that these largely come from the lack of integrated process development to date, a major barrier that the ETI is uniquely positioned to enable to be overcome. In addition to these high level risks, specific risks to the successful outcome of a waste gasification based system development programme are:

- Pre-processing requirements to homogenise variable waste properties limits conversion efficiency gains
- Variety and variability of material and physical properties present in mixed waste stream prevent controllable, stable, robust thermal degradation process
- Cost effective gas cleaning solution not be developed at appropriate scale
- Increased efficiency of larger scale energy from waste facilities negates economic opportunity for small scale systems

In all cases, the processes developed will require gas clean-up technologies to enable the efficient use of the gases produced, and so there would be a risk that developed technologies would be limited in application due to the lack of availability of this enabling technology.

5.1.1.1.5 ETI Additionality and Probability of Success

Due to the nature of the industry to date and the risks associated with a development programme in this area, the ETI additionality for such work is considered to be high. The ETI through its membership and industrial and academic contacts is uniquely positioned to bring together process engineering, chemical engineering, control engineering and mechanical engineering expertise required to develop an integrated system. These disciplines would call on UK and international expertise from thermal, waste, process and mechanical engineering industries to build on the current state of technology.

This unique position and the UK's past record of thermal process development suggest that the ETI's interaction in this area would have a high probability of success. The probability of success would also be dependant on the project structure and participants, the selection of which requires knowledgeable, experienced expert input as to date too much pure research, political and anecdotal expert involvement in selection processes have resulted in failed projects.

5.1.1.1.6 IP Creation Potential

By developing a robust, engineered integrated system based on a range of mechanical and thermal processes, such a project is likely to generate considerable intellectual property (IP) of value to the ETI's members, and the energy from waste and associated process industries. This IP is likely to form considerable knowledge and experience from "learning by doing," as well as hard IP in the form of patents. Anecdotal evidence from the consortium suggests that there are many potential innovations in this space which could be captured by the ETI. This IP relates to the process integration and control aspects, and also to material handing processes, including communition and solid conveying, which are also applicable to other materials handing processes, such as blast furnaces (high temperature processes) and coal (solid materials handling). Likewise gas processing technology and gas property sensing IP would also be applicable to natural gas and other opportunity gases (e.g. coal bed methane, coke oven gas etc). IP associated with gas engine control and operation, including fuel metering, would also have ETI member value. IP associated with gas cleaning development is discussed below.

5.1.1.1.7 UK Manufacturing / Export Potential

Waste is a global issue. Approaches to waste recovery and disposal vary geographically, although the potential to recover energy is largely seen as an attractive proposition. Energy recovery is practised widely across Europe, where the majority of countries have higher energy recovery rates (with associated lower landfill and higher recycling rates) than the UK. In these markets, the ability to recover heat from small, localised systems as well as the system efficiency such scale plants bring are seen as the key value drivers. North America has lower pressures on landfill than Europe, but is driven by energy security and emissions reductions, both of which distributed energy from waste plants would enable. Japan is currently focussed on waste destruction due to a lack of alternative disposal routes. However, recent events in that country have bought energy security to the fore, with a renewed interest in conversion efficiency and utilising a diverse range of fuels to ensure security of supply. In this regard, energy from waste systems capable of significantly greater efficiencies than the incumbent, whilst maintaining the same low level of overall emissions, would have attraction for this market. Lastly, application in developing countries would provide real benefits in tackling energy poverty as well as reducing CO_2 emissions. For such countries, export potential is likely to revolve around the licensing of technology designs and IP for local manufacture and maintenance. Given the link of waste arisings to population, the feedstock availability, and hence market size, for a robust, low cost local energy from waste system in these areas would be significant, and would bring associated employment and development benefits.

Considering these potential applications and demand drivers for a robust energy from waste system with appropriate economics, of which there are very few (if any) economic working processes on the scale envisaged here, the global market, and hence export potential should such a system be developed in the UK, would be considerable.

5.1.1.2 Gasification Gas Cleaning

In the system development programme discussed above, significant technical innovation is required in the gas cleaning technology of “small scale” (i.e. town scale and below) systems to enable the gas to be used as an engine fuel, or for other advanced energy conversion processes. Due to the criticality of this system component (or series of components), the development of such gas cleaning technologies could be conceived as a development project in its own right.

For gasification, the derived gases commonly contain ’tars’ and other contaminants including sulphur and nitrogen species, ammonia and trace metals, as a function of their concentrations in the feedstock materials (Table 14). These contaminants can cause blockages and/or corrosive damage, and can result in downstream NOx, SOx and other emissions above regulated levels. Where blockages or corrosion occurs, system efficiency and availability are impacted, often to the point where lengthy periods of cleaning, refurbishment and replacement are required to enable further system operation.

Element	Average	Element	Average	Element	Average
Oxygen	30 %	Sulphur	0.08 %	Copper	20.5 ppm
Carbon	24.5 %	Chlorine	0.59 %	Chromium	43 ppm
Hydrogen	5.25 %	Bromine	0.01 %	Nickel	9.025 ppm
Silicon	3 %	Phosphorus	0.04 %	Arsenic	5.9 ppm
Iron	3.8 %	Fluorine	0.01 %	Molybdenum	0.964 ppm
Sodium	0.7 %	Magnesium	0.225 %	Antimony	2.15 ppm
Aluminium	1.15 %	Potassium	0.32 %	Silver	0.173 ppm
Calcium	1 %	Manganese	47 ppm	Cadmium	1.15 ppm
Nitrogen	0.55 %	Zinc	71.6 ppm	Mercury	0.07 ppm
		Lead	140 ppm		

Table 14 Typical Waste Properties[26]

The range and type of contaminants in waste gasification gases present a greater technical challenge than AD biogas and the removal to enable gas use in efficient processes are a development opportunity with a number of options. As contaminant levels will vary with feedstock blend and with time, it is important to understand this variability and apply feedstock blend controls and monitoring to ensure that the most cost effective gas cleaning approach can be utilised. It is also necessary to ensure good process control as the levels of certain species, such as NH_3 (ammonia), will vary with changes in operating parameters.

Current gas cleaning systems (where applied) have been shown to operate successfully for periods of time. However, blockages caused by tars and further corrosive damage from gas contaminants requires considerable durations of shut-down as maintenance is carried out. Ultimately this impacts the cost of energy generated (as the useful energy generated per hour is reduced, and hence the required revenue to achieve profitability for that energy is increased), to the point where plant operation is no longer economically viable. These techno-economic

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[26] UK National Household Waste Survey, 1994

factors appear to be the cause of the majority of plant failures to date.[27]

Where current gas cleaning systems may be tailored to the contaminants emanating from a specific, well characterised feedstock (e.g. pulverised coal), a gas cleaning system designed for mixed wastes would need to remove varying levels of contaminants, depending on the composition of the actual input feedstock, which is also likely to change over time as cost and regulatory drivers push for the removal (or inclusion) of certain materials in the waste stream to be processed. Although technologies exist to remove individual gas contaminants, there are little empirical data and evidence from industry that the combination of contaminants can be effectively cleaned to enable the use of the gas in sensitive, but efficient, equipment. Where such a system could be developed from standard gas processing technologies, this is likely to be prohibitively expensive for widespread adoption. In developing a suitably scaled gasification gas cleaning system, the use or disposal of any residues from such a system should also be considered, as they may contain contaminants from the gas which may have a bearing on their disposal options and costs.

The gas cleaning system cleans the gas produced by the main process utilising mixed wastes as a feedstock (producer gas) to enable the gas to be used in downstream applications. This is differentiated from flue gas cleaning following the complete combustion (oxidation) of the wastes (or derived gases), for which technologies exist and are widely in operation to comply with emission regulations. These flue gas treatment technologies are not directly applicable to the treatment of product gas, as the mix of contaminants and the chemical species involved are very different in the reducing product gas environment.

To date, financial drivers from the waste and energy industries have not been sufficient to attract large scale investment in this technology area. These drivers for waste disposal, energy generation and carbon reduction are, however, now focusing on specialised gas cleaning (combined with process optimisation) for the efficient use of waste gasification gases, as illustrated by the increasing volume of analysis and assessment of these technologies currently being published.[28]

If successfully developed, as well as enabling the generation of power (and heat) through gas engines and turbines it is likely that any gas cleaning system could be applied to the production of other products, fuels and chemicals though further downstream processes such as Fischer Tropsch.

5.1.1.2.1 Current TRL Assessment

The TRL of a gas cleaning system is difficult to quantify due to the range of technologies usually combined. These are usually of high TRL technologies from associated industries (i.e. cyclone filters, scrubbers etc. which are all widely deployed (TRL 9) in power generation and process industries). Likewise, the removal of contaminants from large gas flows, equivalent to several tens of MW is practiced widely at oil refineries and natural gas handling facilities. For smaller systems, applicable to all scales of energy from waste plants, the removal of the range of contaminants presented by the gasification of mixed waste streams is often considered the main technical challenge, with few (if any) reference plants commercially operating on biomass or waste. The inclusion of experimental technologies (designs or use of different scrubbing liquids, solid sorbents, activated

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[27] See **Appendix B**.

[28] For example, Review of Technologies for Gasification of Biomass and Wastes, NNFCC 09-008

carbons, etc.), which may be deemed to be a TRL 3 (being tested at lab scale and in some semi-commercial pilot facilities), in development and pilot plants further adds to the complexity of defining a TRL level for "gas cleaning". The lack of an apparent break-through system suggests that at a system level (whether comprising of only high TRL technologies or a combination of low, mid and/or high TRL technologies), the overall TRL may in actuality be deemed to be "low," estimated at TRL ~0-4).

5.1.1.2.2 Prospective Technology Development Process

A wide range of products, including tars and corrosive chemical elements and compounds, result from the gasification of mixed waste feedstocks. The successful development of a robust, low cost gas cleaning system will likely involve innovative, low energy integrated gas cleaning approaches to reduce residual contaminants in fuel gases sufficient to meet the inlet requirements of the downstream systems. Such schemes may involve smart use of particulate filtration with injected solids and the use of catalysts. Strategies for recovering the energy content contained within the tars may include the processing of tars for alternative uses or through their cracking for recycling into the gas stream. The identification of the carbon benefits associated with town and village scale gasification suggests that system scalability will be a critical success factor. Similarly, system efficiency is a key enabler for carbon savings; given that thermodynamic limitations dictate the efficiencies of the gasification and downstream technologies, any further energy load demanded by the gas cleaning system will directly impact the system efficiency. Therefore, the requirements of the gas cleaning will have to balance the variability of the feedstock with the downstream use of the product gas to develop optimised systems at the required scale.

The cost and performance targets for a gas cleaning system can only be judged against those of the entire waste to energy system in which gas cleaning is a single, critical, element. The gas cleaning system must be of sufficiently low cost and high efficiency to enable the rest of the system to reach its cost/performance metrics, as defined in relation to the gasification system above. The lack of precise establishment of gas cleaning requirements for a range of downstream technologies, and the cost/cleanliness trade-off, is a current barrier to system development, and hence should form the first part of the experimental work to be carried out in this development work. For the development of the gas cleaning technology in its own right, the following major development steps are foreseen:

1. Provide a national facility with access to real waste gasification gases at a scale that is relevant for commercialisation.
    a. Bring together engineering resources (people and equipment) that can identify and engineer the requirements for the gasification and gas cleaning.
2. Establish gas quality requirements for downstream utilisation
    a. Establish linkage between gas composition/contaminants and engine effects, link to engine operation costs for gas cleaning level/cost trade-off.
3. Thermo chemical process engineering assessment of gas cleaning requirement; system design and specification
4. Pre-screening pilot scale evaluation of potential gas cleaning technologies (in parallel to above activities)
    a. Desk-top and experimental evaluation of technologies
    b. Validation of performance claims under range of simulated conditions representative of full scale operation

5. Gas cleaning system design, build, install, test
    a. At full scale based on small scale test results
6. System development and optimisation
7. Demonstration of prolonged operation duration to establish and verify overall cost of energy

These facilities should build on, or be closely linked to, the gasification assets described in Section 5.1.1.1.2. The steps outlined above have estimated costs and durations as set out below:

- Equipment capital: £5 million/technology
    - Purchase of power generation technology £1M - £2M, with instrumentation and spares
    - Gas-Cleaning: £3M - £4M per technology
    - Require supply of "real" gasification gas
- Testing and development of prototype development equipment: £1 Million per annum
    - Consumables, materials, fabrication etc.
- Staff to operate and manage the facility: £2 million per annum
    - 5 skilled engineers @ £1000/day, 250 days/year: £1.25M
    - 5 technicians @ £500/day, 250 days: £0.625M
    - Secretarial, security staff etc.
- Procurement and construction of facility and prototype development equipment technologies for installation: 2 years
- Testing and development of prototype development equipment: 3 years

Estimated by consortium that development of a robust gas cleaning system at an appropriate scale from TRL ~4 to a TRL of ~6 may be achievable in around 5 years. It is likely that any system developed would also be applicable to biomass gasification.

5.1.1.2.3 Concurrent Development Activities

The nature and cost-effectiveness of gas cleaning is critical. Drivers for increased efficiency as well as manufacturing capabilities are driving for more stringent gas quality requirements from downstream equipment (e.g. catalysts, fuel cells and engines), which in turn drives further demands for higher levels of gas cleaning. These drivers have led to much work in the area of gas cleaning, both in the UK and globally, as evidenced by the Technology Landscape Assessment and Conversion and Resource Efficiency work (see Appendices B and C). Despite these efforts, a highly robust and cost effective gas cleaning system for small scale applications utilising mixed wastes as a feedstock appears elusive.

Of the most prominent activities, exact operational data is difficult to ascertain due to the commercially sensitive nature of such data; ITI Energy Ltd (a spin-out from Newcastle University) claim to be able to process MSW and have been granted planning and permits for several projects, although their first project in Wick appears to have been closed down due to operational problems, apparently between the gas produced and the power generation equipment, hinting at gas cleaning shortcomings. Additionally, Biomass Engineering Ltd claim to have an operational site in Banbury, although again operational data is scarce. Pyrolysis of mixed waste to produce a methane-rich gas is also being investigated commercially (16 UK active companies identified by CARE). However, as also found by this project (WP2), the gas produced, whilst higher in calorific value, contains even higher levels of contamination than from gasification. This is also evident from some of the higher profile pilot plants employing this technology, where consortium members have been directly approached with requests about gas quality and cleaning requirements.

One of most major development programmes of current times is the “Ultra Clean Gas Concept” project, being led by VTT with partners FWE Oy, Neste Oil, Vapo, Andritz, Technical University of Helsinki, StoraEnso, UPM, M-Real, Metsä-Botnia and PVO in Jyvaskyla, Finland. The project is seeking to develop an optimised pressurised oxygen-steam fluidised-bed gasification process capable of processing a wide range of feedstocks: woody biomass, agrobiomass, peat and waste derived fuels. The main focus of the project is on optimised gas reforming, dirty shift and ultra cleanup technologies to enable liquid biofuel production to be integrated into pulp and paper industries. Launched in 2004, the project is currently experiencing considerable technical issues relating to the removal of tars from the gas stream, once again showing that gas cleaning is a major technical challenge in enabling the use of gasification derived gases for high value energy processes.

5.1.1.2.4 Technology Development Risks

As noted above, gas cleaning has been identified as the critical component in efficient gasification systems for some time, and as such has been, and is, the subject of a considerable body of research and development activity. Despite this activity, it is considered by the consortium that many approaches remain unexplored, and that to date only limited process engineering rigour has been applied. However, it should be recognised that there is some residual risk that any ETI funded activity in this area may not be able to provide the technical solution to enable gas quality requirements to be met in a cost effective, and energy efficient, manner.

5.1.1.2.5 ETI Addtionality and Probability of Success

The nature of the process orientated challenge of gas cleaning at the scales required for gasification based energy from waste systems presents a high opportunity for ETI additionality. It is the view of the consortium that to date a lack of process engineering rigour has resulted in poor system development, to the extent that gas cleaning remains unproven at scale. By bringing together of UK and international process engineering, chemical engineering, control engineering and mechanical engineering expertise, the ETI is well positioned to enable the development of a robust gas cleaning solution.

5.1.1.2.6 IP Creation Potential

The development of a robust gas cleaning solution would entail the development of considerable IP in the areas of gas processing and associated materials handling. As for gasification system development, this area is expected to be a rich source of IP, with the opportunity for innovation as well as development. IP created through experience as well as hard IP (such as patents) are likely to be applicable to a range of gas based applications, and so also have value and applicability in natural gas and other gas industries, particularly at a distributed energy scale.

5.1.1.2.7 UK Manufacturing / Export Potential

The process required to develop a suitable gas cleaning solution is likely to comprise of a collaborative approach involving large companies, SMEs and academic institutions. This combination of organisations is likely to lead to entrepreneurial off-shoots to commercialise the technology. Gas cleaning is an enabler for the successful deployment of gasification systems. As such, its development would allow this global market to be accessed, with a strong UK opportunity to leverage industrial and academic process expertise for the ongoing development of gas cleaning technology and gasification based energy from waste systems.

5.1.2 Anaerobic Digestion

Anaerobic digestion plants have been identified as the best route to process wet bio wastes. Although AD technology is becoming established, it currently has relatively low overall energy conversion efficiency for the size of plant. It is concluded that AD for energy production should be targeted with a view to increasing the yield of gas per unit of feedstock and increasing process intensity to reduce plant size. This may potentially be achieved through material pre-treatment for better accessibility to its micro-structure, and/or through the development of low cost continuous AD processes.

To deliver the potential carbon savings identified there are clear opportunities for further process and technology development, especially for technologies and processes which are more efficient than the current ~13% gas yield. Current batch processes usually have an adaptation time of ~3-6 weeks between feedstock types. Whilst the rate of transformation of microbes cannot be readily altered, the use of continuous AD process is likely to enable compact and cost effective deployment at smaller scales. The technology is scalable and economies of scale of downstream usage are considerable, but reactor costs would require significant reductions at smaller scales, or much greater conversion efficiencies, for cost effective plants to be developed for village and rural scales (less than 5kt/year). In terms of feedstock diversity and contributing to energy supply, AD is only applicable to appropriate biogenic wastes, and is most efficient when applied to high moisture content materials to allow the microbes to transport. If scaled down to a domestic level, sewage that is currently managed in domestic septic tanks would also be available for treatment, and the methane emissions there from would be captured.

5.1.2.1.1 Current TRL Assessment

AD is a well-established technology that has been deployed around the world for many years. The AD process itself is at a high TRL, although small scale AD systems, especially those operating continuously or in a controlled, high efficiency manner, are still under development and may be judged to be at TRL of ~4. However, the potential for acceleration is thought by the consortium to be considerable, with a requirement for evidence of a reliable medium term operation at an appropriate cost to enable commercial deployment.

Although the core technology is commercially available, the inclusion of H_2S in the gas produced leads to the corrosion of downstream gas usage devices, increasing their operational costs as well as raising potential safety risks. Although this work showed that the addition of small volumes of biogenic dry wastes (e.g. paper and card) can be used to control the H_2S production rates, the gas cleaning of biogas poses an ongoing challenge. Scrubbers and filters are available for the removal of H_2S from biogas, although their effectiveness is dependant on the concentration of the contaminant in the gas. As such, H_2S removal does not present as great a current barrier as for gasification gas cleaning, although further development could reduce the cost, and/or increase the effectiveness of H_2S removal technologies, decreasing the cost of energy generation using anaerobic digestion.

While the primary use for the digestate residue is soil beneficiation as a fertiliser, where this is not possible or acceptable the residue could be used as an additional feedstock for parallel gasification or pyrolysis processes after drying or blending to meet feedstock moisture constraints. This integrated approach requires further technical validation, and should be considered under the development of integrated facilities as discussed in Section 5.1.3.

5.1.2.1.2 Prospective Technology Development Process

The efficiency of conversion of wet waste materials may be increased by enabling greater bacterial access to the material microstructure, and through process development and optimisation. To develop highly efficient systems, both of these aspects should be examined in combination. As such, the major development steps to improve the conversion efficiency of AD processes are:

1. Process mapping
    a. Lab scale testing of each step of the AD process (feedstock to biogas) to determine influencing parameters and trade-offs.
    b. Investigation of waste pre-treatment processes with regard to biogas yield and process residue value
2. Reactor design development and validation
3. Process control integration
4. Testing and optimisation

Such a programme is estimated to have a total cost of around £5M with a duration of ~3-5 years. It is thought that a ~TRL 6 process can be achieved in this timeframe. This would allow for the initial demonstration of a high yield, developed AD system at scale. In terms of performance, Table 15 details the range of cost and conversion values that anaerobic digestion systems are estimated to be able to achieve. These values include their current state (5% conversion efficiency, £100/tpa) to enable their cost of energy to be modelled (as detailed in Section 6) in the case that technology improvement is not found to be feasible.

		Low	Middle	High
Capital Cost [£/tpa]	Electricity	100	150	200
	Heat	100		
Operational Cost [£/kWhr]	Electricity	0.02	0.05	0.1
	Heat	0.01		
Conversion Efficiency [%]	Electrical and Heat	30%	33%	35%
	Waste Feedstock Mass Conversion	17%	30%	45%

Table 15 Anaerobic Digestion Projected Technology Performance Ranges

5.1.2.1.3 Concurrent Development Activities

Due to the UK, and global, interest in AD technologies to mitigate un-captured methane production, there are a large number concurrent development activities, leading to AEA to state “there are countless enterprises carrying out various development projects in AD of wastes.” Some UK based examples are:

- Scottish Enterprise are currently funding the “Seaweed Anaerobic Digestion” programme, involving Abertay, Newcastle University, Glasgow Caledonian University, Zebec and B9 Organic Energy
- A number of UK universities, in addition to those listed above, have current active AD research programmes. Specifically, Cranfield University has a strong history of working with the water industry, and Southampton and Harper Adams Universities both collaborate with Biogen Greenfinch in the development of AD systems.

- CPI (consortium member) is running an eco-innovation programme on "MiniAD," - developing a small-scale, demonstrative anaerobic digestion plant designed to assist meat processors dispose of hazardous waste and simultaneously generate renewable energy, produce safe agricultural fertiliser and deliver water.
- CPI has a 'plug and play' anaerobic digestion development centre which is a small scale open access facility for developers. It has pre-treatment, vertical reactors, horizontal reactors and post treatment facilities.
- UK has strong base in process industries and innovation in process technology, but little has been focused on AD.
- In addition to the larger scale technology development above, some small and micro scale AD technology improvements are currently in development such as the CPI and ECO innovation project.

5.1.2.1.4 Technology Development Risks

The following risks apply of the ETI were to fund a project to develop AD technologies:

- Increased yield can not be achieved
- Cost increase outweighs yield increase
- Overlap with currently occurring work e.g. CPI Eco-Innovation Project
    - This may present an opportunity to leverage such activities

5.1.2.1.5 ETI Additionality and Probability of Success

The broad range of activities currently ongoing in the development of efficient AD processes would suggest there might be limited additionality for ETI activities in this area. However, it was remarked at the ETI EfW technology stakeholder meeting on 6th June 2011 that the coordination of the ongoing activities presents a high potential for ETI additionality in this area. In addition, by enabling the bringing together of cross disciplinary skills of process design, equipment development, process integration and control engineering with chemical and biological engineering, the ETI is well placed to enable process development and optimisation.

5.1.2.1.6 IP Creation Potential

Although there are many patents in the field of AD there is still significant opportunity for further IP in process steps and application. The process innovation required to increase the efficiency of AD processes is likely to lead to the creation of significant amounts of IP. Particular opportunities have been identified around control engineering and integration, as well as in feedstock flexibility and blending with potential to leverage technology for adjacent feedstocks (e.g. energy crops) and alternative energy vectors (e.g. biogas grid injection). IP is also likely to be applicable to the production of liquid fuels.

5.1.2.1.7 UK Manufacturing / Export Potential

The market and supply for small scale units are currently immature, though developing, and present an opportunity for the UK to lead the market. The global availability of livestock slurries, particularly in areas with intensive farming practices, presents a potential export market for suitable scale, low cost system products. Germany and Denmark are the current leaders in AD/biogas technology, with the majority of farm based UK sites currently using imported equipment and expertise. As such, the development of a UK based AD industry would lead to domestic and export opportunities. There are UK skills to build on, with Biogen Greenfinch having a strong position in UK food based plants, and several University groups in AD research.

5.1.3 Integration of Gasification and AD Facilities at Community Scales

The development opportunities described above present significant technical developments and would realise the associated carbon, energy cost and robustness (security of supply) benefits detailed in this report. These benefits may be maximised through the subsequent integration of the developed technology systems into a highly flexible waste processing and energy generation system. This presents an opportunity to develop and demonstrate integrated Distributed Energy (DE) systems of technologies that can service smaller communities with a particular emphasis on town and village scale systems. Combinations of technology are likely to be AD, gasification, and where appropriate, incineration, with upstream and downstream processing. This approach could reduce emissions for both electricity production and in CHP systems.

Large-scale waste processing technology is currently available for city scale installations, which combine waste sorting, AD, composting and recycling with residual disposal. However, large integrated plants do not necessarily provide operational flexibility, as a large plant processing 100 kTpa of fuel will require a continuous process to cope with the continuously arising waste. The evidence indicates that there is an opportunity to develop integrated DE systems of technology that can service smaller communities at around 50 KTpa or less. The economics will come from lower cost technologies driven by a production line approach to large volume production.

One opportunity for integration would be the gasification of AD digestate that cannot be used as a fertiliser or put back onto the land. The digestate could be used as a “balancing” material, ensuring the gasifier always has sufficient supply in times of variable waste, as digestate volumes and energy content depend on the amount of waste digested and the digestion efficiency. Small modular plants at the town and village scale with appropriate instrumentation and control also offer the required flexibility to meet both waste supply and demand profiles. The opportunity for fuel diversity with a well designed integrated system would be high, and is likely to include a range of separated and mixed feedstocks including MSW, C&I waste, food waste, wood waste, raw biomass and agricultural residues. The integrated plant should be designed to maximise adaptability potential and minimise the time to adapt to another fuel source. Although there is no ‘definition’ of such an integrated system, a potential technology set with material flow paths is represented schematically in Figure 12.

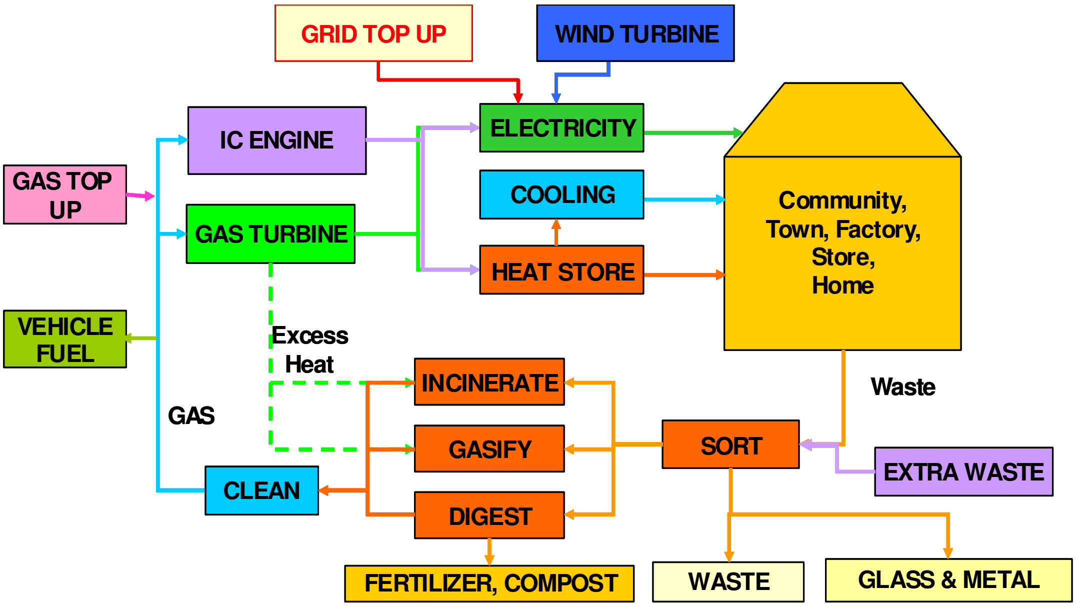

Figure 12 Schematic representation of an integrated EfW system

5.1.3.1 Prospective Technology Development Facility

The development and demonstration of integrated systems would build on the development of the thermal (gasification) and AD based integrated sub-systems, although the development of these technologies in an integrated system is likely to provide additional benefit from engineering synergies. Either for their integrated development, or for the integration of the systems, a multi-configurable facility would be required, where the component and system technologies can be operated concurrently at their appropriate scales, and co-developed to optimise the system performance.

A facility to integrate these technologies could carry out the development opportunities outlined above, as shown schematically in Figure 13. Such a facility would enable full system development, from the incoming waste (potentially including sorting waste at the facility) to electricity and heat generation, and would be required to contain each of the process elements (waste reception and potential sorting, pre-treatment, treatment, post-treatment and energy generation) for full systems level development and demonstration. The consortium estimates that based on operational thermal/gasification and AD systems, an integrated system may be developed in 3 years, with an additional cost (to the core conversion technology system development) estimated to be around £20m to £30m. This cost is based on the time (manpower) and materials (material and fabrication) required to integrate and optimise the total system Such a system should seek to lead to a full scale, commercial application at the appropriate scale to support a community as a second stage demonstrator.

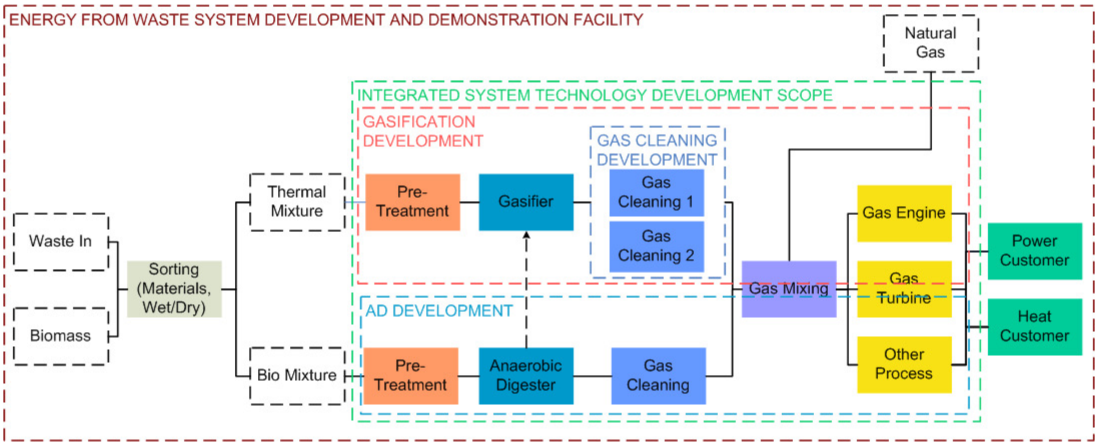

Figure 13 Schematic of Integrated System Development Facility

The system of four integrated development activities shown in Figure 13 could form the basis of a set of ETI programmes to address the recommendations of this project. These programmes and their priority order are summarised in Table 16.

Programme	Capital	Project Costs	Timescale
Advanced Thermal Processes	£10m - £15m	£10m	3-5 years
Gasification Gas Cleaning	£5m	£3m	2-3 years
Anaerobic Digestion	£3m	£2m	3-5 years
Integrated Facility	£15m - £20m	£5m - £10m	3-6 years
Total	£33m - £43m	£20m - £25m	

Table 16 Recommended Technology Development Opportunties

5.2 Out of Scope Opportunities

In addition to the development opportunities detailed above, a number of additional opportunities were identified from the test and modelling work which would increase the commercial viability of energy from waste systems. These additional opportunities fall outside the scope of this project, but are either covered by other ETI projects, or will be more thoroughly detailed in additional work commissioned by the ETI. In all cases these developments, and their associated emissions and cost benefits, are dependant on the technical viability of the core energy from waste conversion technology systems.

5.2.1 Low cost heat networks

Using the heat produced during the processing of waste materials and/or the power generation from the derived energy enables further carbon savings through offsetting the use of natural gas for heating applications. There are also a number of community CHP plants or community heat supply systems operating in the UK – for instance, in Aberdeen, Milton Keynes, Byker (Newcastle), Nottingham, Sheffield and Woking.[29] However, high level modelling carried out in Work Package 3 shows that utilisation of 80% of the heat produced at a city scale would enable an annual CO_2 saving of between 120kt/yr and 150kt/yr from the offset of natural gas. The development of the heat networks to enable these reductions is technologically separate from that to enable energy from waste, although the integration of established CHP technologies such as gas engines and turbines would facilitate heat usage.

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[29] The assessment of the additional cost of capital required for a plant to develop, or connect to, a heat network are out of scope of this project are under assessment in other ETI activities (The Macro DE project).

5.2.2 Low cost processes to convert syngas into chemicals or fuels

The gasification technologies examined here can be used to produce gas which may also be used as syngas for the production of chemicals or transport fuels. Investigation of the carbon benefits associated with these conversion paths fall outside the scope here. In all cases, due to the capital requirements associated with chemical and fuel production plants (and non-scalability of these plants), these benefits are only likely to be applicable to city scale waste arisings volumes, where a large scale gasification process is being used to produce a large volume of high quality syngas. A number of companies are developing a range of technologies, but a more structured public-private partnership to drive value creation may be of value to developing this market further. This opportunity is being investigated further in a short focused follow-on programme.

5.2.3 Pyrolysis for liquid fuel production

Pyrolysis for the production of liquid fuels has not been explicitly examined due the requirement for a segregated, well characterised feedstock stream, and identified issues associated with the use of the produced oil, even from such streams. These issues include the acidity of the oil (typically pH ~2 - 3), its high viscosity and its temporal instability due to the presence of oxygen (derived from the feedstock) in the oil. Techniques to overcome these shortcomings are under development, such as hydrogenation, and may become more developed and cost effective should hydrogen become a more readily available and lower priced commodity. The development of these upgrading technologies may provide an adjacent TDO, although clarification of the carbon benefits associated with this opportunity would require further investigation. This opportunity is being investigated further in a short focused follow-on programme.

5.2.4 Gas Grid Injection

Either purified methane from biogas or upgraded syn-gas could potentially be injected into the UK gas grid. However, a number of technical and regulatory barriers currently present barriers to this. This potential outlet for the products of the energy from waste technologies recommended for development could add further value to their development, and this opportunity is being investigated further in a short focused follow-on programme.

5.2.5 Integration of Carbon Capture and Storage

Additional emissions benefits from using energy from waste and biomass technologies may be accrued through the capture and storage of any carbon which would otherwise be released from the processes, adding further value to the technologies recommended for development. The opportunity for capturing these emissions, and the technical challenges associated with the additional requirements, are being investigated further in a short focused follow-on programme.

5.2.6 Other potential areas of development

A number of general technology enablers have been identified that could provide additional value. These adjacent areas are not development opportunities in their own right, but their consideration should be incorporated into any subsequent activities. From all of the opportunities highlighted above and the associated generic enablers, such as feedstock control and monitoring, it is clear that successful EfW systems will only come from a detailed knowledge of waste arisings, the quantification of their physical, chemical and economic properties combined with energy conversion systems which are designed as optimised systems of components and not treated as a series of process steps which are ‘bolted’ together.

In addition to the technology focused recommendations, it is important to consider a number of economic and social dimensions and possible work streams. These include:

5.2.6.1 Investment models

Work to develop new investment models for EfW is required. Current investment models are tied to large plants that can prove they have secure low cost feedstock supply for enough years to ensure that the investment in the facility pays back with little or no risk to the investor. This approach to financing is unlikely to work with smaller scale distributed technologies and it is suggested that investment options are studied to assess options such as leasing, third party investment based on off-take or supply agreements and outright purchase by individuals or communities.

5.2.6.2 Supply chain development and value chain creation

There is a need to support the development of a supply chain that can create value for the UK. This covers undertaking research to supporting organisations meet market demands.

5.2.6.3 Community and stakeholder consultation

It is important to develop consultation processes with communities and stakeholders on the development and application on EfW, especially when looking at the small scale scenarios. As part of a wider public understanding of science and technology approach, these need to be undertaken in parallel to the development of the technologies as will ultimately influence the market success of EfW technologies in the UK.

5.2.6.4 Policy impact assessment

There is a need to consider the impact of EfW technologies on energy and waste policy at local, regional and national levels. In addition, the development of EfW technologies needs to be assessed in relation to wider economic development and regional growth strategies which require a mix of public-private investment and actors.

The development and use of EfW technologies needs to be assessed in relation to technological, economic and social factors. Whilst some of these variables can be modelled, others, such as energy security and legislation,[30] are more challenging. Nonetheless, the results and findings presented in this report - based on a comprehensive modelling and scenario analysis on how EfW technologies can be used to meet waste and carbon reduction needs – point to the potential for exploiting EfW technologies in the UK.

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[30] See AEA report in **Appendix B**.

6 Technology Development Targets and Cost of Energy

To determine the potential for energy from waste technologies to be deployed, and for their associated emissions reduction benefits to be achieved in practice, analysis was carried out into the potential range of costs of energy generation from waste. The cost of energy generation is dependant on a range of controllable (i.e. a function of the technology) and uncontrollable (i.e. external factors which cannot be directly affected by technology development) factors. These factors, and their impact, are outlined in Table 11.

The controllable factors are those which are directly influenced by the technology. As such, and as detailed in Section 4 of this report, their value is open to projection based on the potential for the development of advanced energy from waste technologies. For each of the thermal (incorporating gasification and pyrolysis of mixed wastes to produce a gaseous fuel) and biological (anaerobic digestion) technologies considered in this project, their “to be developed” state is projected in terms of low, medium and high values (and intermediate for conversion efficiency). These values, as derived in Section 4, are summarised below in Table 17 and Table 18 for the advanced thermal (gasification) and AD technologies respectively.

		Low	Middle	High
Capital Cost [£/tpa]	Electricity	350	500	650
	Heat	100		
Operational Cost [£/kWhr]	Electricity	0.02	0.05	0.1
	Heat	0.01		
Conversion Efficiency [%]	Electrical and Heat	30%	38%, 50%	80%
	Waste Feedstock Mass Conversion	50%	65%, 80&	100%

Table 17 Projected and Assumed Values Impacting Cost of Energy (Advanced Thermal Conversion Technologies)

		Low	Middle	High
Capital Cost [£/tpa]	Electricity	100	150	200
	Heat	100		
Operational Cost [£/kWhr]	Electricity	0.02	0.05	0.1
	Heat	0.01		
Conversion Efficiency [%]	Electrical and Heat	30%	33%	35%
	Waste Feedstock Mass Conversion	17%	30%	45%

Table 18 Projected and Assumed Values Impacting Cost of Energy (Advanced AD Technologies)

Again, the large number of variables relating to technology performance would make assessment, and presentation, of each possible combination of factors uninterruptable. As such, a number of scenarios for the combination of technology factors outlined in Table 17 and Table 18 have been assessed to represent the range of possible costs of energy. These cost of energy scenarios, along with the combination of factors of which they are comprised, are summarised in Table 19 with the high and low range values for the thermal (gasification) and digestion technologies summarised in Table 20 and Table 21 respectively.

	Incineration	Advanced Thermal Power	Advanced Thermal CHP	Advanced Thermal Heat	Advanced AD Power	Advanced AD CHP
Capital Cost [£/tonne/year]	500.00	500.00	500.00	500.00	150.00	150.00
Operational Cost Electricity [£/kWhr]	0.05	0.05	0.05	0.00	0.05	0.05
Operational Cost Heat [£/kWhr]	0.00	0.00	0.01	0.01	0.00	0.01
Operational Cost Total [£/kWhr]	0.05	0.05	0.06	0.01	0.05	0.06
Conversion Efficiency Electricity [%]	22% Large Scale 15% Small scale	30%	30%	0%	10%	15%
Conversion Efficiency Heat [%]	0%	0%	50%	80%	0%	15%
Cost of Capital [%]	7%	10%	10%	10%	10%	10%

Table 19 Technology Performance and Cost of Energy Scenario Factors (Mid Points)

	Power			CHP			Heat	
	High	Low		High	Low		High	Low
Capital Cost [£/tonne/year]	650.00	350.00		650.00	350.00		500.00	350.00
Operational Cost Electricity [£/kWhr]	0.10	0.02		0.10	0.02		0.00	0.00
Operational Cost Heat [£/kWhr]	0.00	0.00		0.01	0.01		0.01	0.01
Operational Cost Total [£/kWhr]	0.10	0.02		0.11	0.03		0.01	0.01
Conversion Efficiency Electricity [%]	20%	30%		30%	30%		0%	0%
Conversion Efficiency Heat [%]	0%	0%		50%	50%		80%	80%
Cost of Capital [%]	16%	7%		16%	7%		16%	7%

Table 20 Technology Performance and Cost of Energy Scenario Factors (Thermal Technology High and Low Points)

	Power			CHP	
	High	Low		High	Low
Capital Cost [£/tonne/year]	200.00	100.00		200.00	100.00
Operational Cost Electricity [£/kWhr]	0.10	0.02		0.10	0.02
Operational Cost Heat [£/kWhr]	0.00	0.00		0.01	0.01
Operational Cost Total [£/kWhr]	0.10	0.02		0.11	0.03
Conversion Efficiency Electricity [%]	5%	20%		15%	15%
Conversion Efficiency Heat [%]	0%	0%		15%	15%
Cost of Capital [%]	16%	7%		16%	7%

Table 21 Technology Performance and Cost of Energy Scenario Factors (AD Technology High and Low Points)

The cost of energy was calculated for each scenario (set of variables) outlined in Table 19, with high and low boundaries (in terms of performances variables, not probability or confidence in values) listed in Table 20 and Table 21 for the advanced thermal and AD technologies respectively. In this respect, the cost of energy was that which it would cost to generate each unit of useful energy (heat or power), based on the operational costs and paying back the interest (cost of capital) on the capital over an assumed 20 year lifespan of each technology system. Additional assumptions on the rate of capital payback and profit could be applied to determine a further price of energy, although such assumptions were beyond the scope of examining the core factors affecting the cost of energy. The cost of energy was calculated, as advised, on a "zero" cost/value for the waste; hence, a zero cost/value of waste assumes that no cost is incurred *by the waste to energy plant* in its transportation. Other waste financial values (including assumptions for the cost of transportation) can be investigated in the dynamic tool on which this chart is based, and which also forms a deliverable to this project. The core cost of energy generation for each of the central scenarios outlined in Table 19 is shown below in Figure 14, with the error bars showing the high and low boundaries. For Incineration, the current cost of energy generation is plotted based on the cost and performance data collated for the project (and corresponding to Figure 9). The cost of energy generation with a gate fee of £40/tonne is also superimposed to indicate the sensitivity to the feedstock value. For the advanced thermal and AD technologies, Figure 14 shows the cost of energy generation at the potential technology performance and cost levels as are projected to be achievable following technology development. As discussed in Section 5, for the thermal technologies, these performance levels have yet to be demonstrated. For the AD technologies, current operational systems exist, with cost and efficiency metrics as plotted in Figure 11 (Holsworthy Plant); the current cost of energy generation from this technology is indicated (without a gate fee), with further projections of the cost of energy which may be achieved through increasing the technology conversion efficiency and/or reducing its cost. The current average retail price of UK electricity has also been superimposed to present a relative comparison, although it should be reiterated that the cost of energy generation relates to *any* form of energy at the listed technology system factor cost and performance values. The cost of energy is widely expected to increase in the future, although it is beyond the scope of this project to attempt to project future electricity (or other energy forms) cost/price levels; the future direction of energy prices is represented by the upwards arrow, although its upper point is purely arbitrary, and should not be taken as a projection of future costs, merely as an indicator of the direction of energy prices in the future.

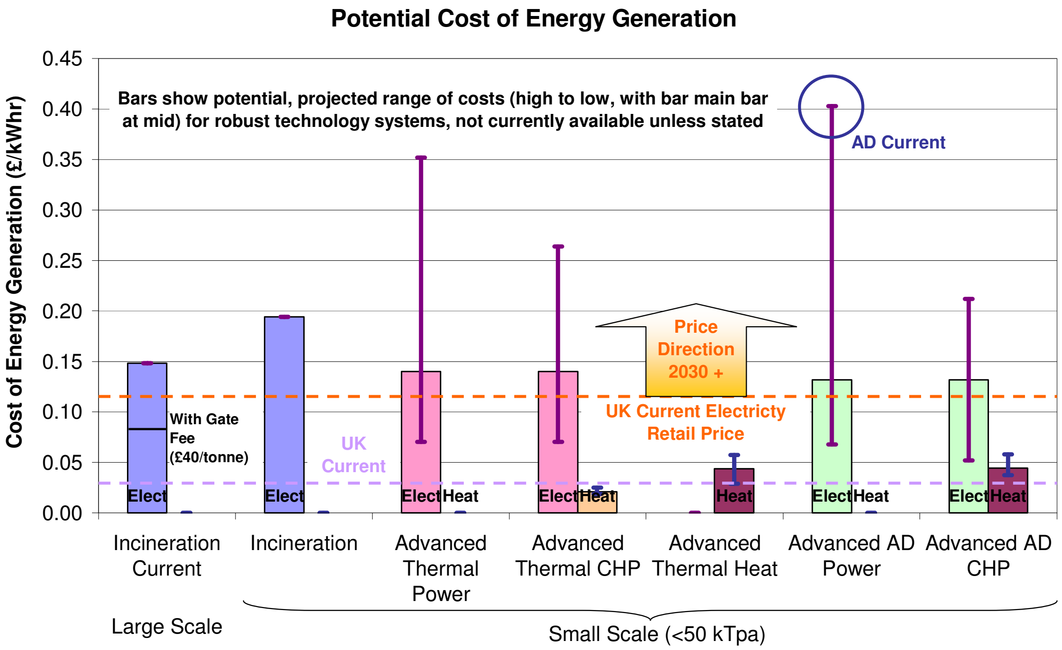

Figure 14 Cost of Energy Scenarios

The cost of energy projections in Figure 14 show that the conversion efficiency and cost of capital are the key controllable factors in reducing the generated energy cost. As such, high electrical conversion efficiency technologies with low capital costs (as relates to the values in Table 19) are likely to be competitive with current electricity prices. As prices are largely expected to rise (in real terms) going forward, and in the 2030 timeframe on which the technology projections are based, these technologies are predicted to become increasingly competitive if they can be developed to the required state. As stated above, this assessment of advanced technologies is based on a valueless feedstock; further economic advantage would occur with gate fees, which might well be the case in practice, particularly for un-processed feedstocks. Based on these technology performance and cost projections, at a local scale (where heat may best be utilised), advanced energy from waste technologies are projected to enable a generation cost reduction of £0.05 /kWhr as compared to small scale incineration (proven technology). At a generation capacity of 25 TWhrs this equates to a **UK annual saving of £1.25BN**. Compared to large scale incineration, generation costs are projected to be approximately £0.01 /kWhr lower using advanced technologies (mid point), resulting in UK annual savings of £250M. Small scale plants would have the additional benefits of also reducing in waste transportation costs. Assuming a saving of £10/tonne,[31] the additional saving would be £250M, resulting in a total UK annual saving of £500M.

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[31] Waste industry "rule of thumb" for any waste management operation, including transport – assumption is that one "operation" is saved (i.e. transportation from local waste handler to large incineration facility).

7 Conclusion and Recommendations

7.1 Conclusion

Waste is, by definition, material which is no longer useful.[32] As the product of processes and activities, it is in its nature highly variable both in type and volume. Predicting its future arising requires an implicit prediction of the nature and amount of activity taking place, and the waste generated from those activities, all of which are highly uncertain at a macro, national scale over any time periods. To attempt to bound the range of possible future waste availability, the residual waste arisings drivers of volume produced and amount "recycled" were projected to impact current per capita arisings. By aggregating populations over cities, towns, villages and rural scales, a waste embodied energy content range of **500 to 1,000 PJ per year** (~12 – 24 Mtoe) is projected to be available in the 2030 timeframe.

The amount of energy which may be utilised from this waste is again dependant on a number of factors, including the amount of residual waste available for energy generation, and the efficiency with which the embodied energy is converted to useful heat, electricity of other energy vectors. Currently achievable and theoretical future conversion efficiencies vary between dry and wet wastes, and are highly dependant on the amount of heat which may usefully be recovered from conversion processes. Superimposing projected values for a range of low to high waste availability and conversion efficiencies (both current and future potential) on the projected waste arisings showed that the amount of useful energy that might be generated from waste (both heat and power), nominally in 2030, ranges from **5 to 230 TWhrs**.

The emissions benefits which may be enabled from using waste to generate energy are dependant on the emissions intensity of the source that is offset by the waste, and the emissions intensity attributed to the waste itself. The emissions intensity of waste may be taken as an absolute value attributed to its entire volume, to be accounted for as emissions neutral over its entire volume, or for only the emissions for the non-biogenic volume to be attributed to the overall volume. Based on offsetting centralised grid power generation with a projected carbon emissions intensity of 50 g/kWhr,[33] the projected net CO_2e impact of energy from waste ranges from **-5 to -18 MTCO$_2$e/year.** Additional benefits would accrue from the offsetting of heat generation from the recovery and utilisation of heat from energy from waste processes, and by increasing their conversion efficiency,

The commercial and technical assessment of energy from waste technologies showed that for dry wastes, the currently used technology is best suited to large scale applications due its use of non-scalable steam cycles, and are economically marginal. Higher conversion efficiencies, including enabling the use of heat, may be theoretically achieved through smaller, local scale advanced thermal systems, but their technical state is such that long term, robust operation on waste feedstocks is yet to be demonstrated. Technical barriers still present relate primarily to an effective gas cleaning solution, and to system integration in respect of optimising the total efficiency and operation, including the gas cleaning and downstream gas utilisation. If these barriers were to be overcome, potentially as a result of ETI funded development work, **energy generation costs** from waste (without a gate fee) are projected to be **~£0.14 /kWhr**. This is a reduction of £0.05 /kWhr as

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[32] google search: "definition waste"

[33] Committee for Climate Change projection for UK electricity grid intensity in 2030

compared to the current state of small scale incineration technologies, and is projected (mid point), to equate to a **UK annual savings of £1.25BN.** Compared to large scale incineration, the annual saving is projected to be £500M.

For wet wastes, Anaerobic Digestion is becoming established with food and other biogenic wastes, building on experience in the water sewage treatment industry. However, gas yields, and hence conversion efficiencies are low, and at smaller scales low economies of scale mean that capital costs are currently relatively high.

Integrated waste to energy facilities scaled to communities, which seek to maximise the resource efficiency of waste to heat and electrical (and other) energy for that community, offer potential additional economic and environmental benefits in fitting with the UK's localism agenda, but require development and demonstration for public engagement.

7.2 Recommendations

The emissions and economic benefits of the deployment of energy from waste systems which are able to maximise the efficient use of locally occurring residual waste resources is currently hampered by a number of technical barriers. This project has identified target areas of work suitable for ETI funding to overcome these barriers, and thereby enable the demonstration, and eventual commercial deployment, of these technologies. Specifically, the areas which require further development are:

- Distributed scale advanced thermal integrated systems for wastes
- Cost effective gasification gas clean-up, in accordance with a system solution
- Low cost, high efficiency distributed scale integrated AD systems
- Integrated distributed energy from waste facilities incorporating: thermal and AD technologies to maximise resource efficiency.

Potential costs of the programme are summarised in Table 22 below:

Programme	Capital	Project Costs	Timescale
Advanced Thermal Processes	£10m - £15m	£10m	3-5 years
Gasification Gas Cleaning	£5m	£3m	2-3 years
Anaerobic Digestion	£3m	£2m	3-5 years
Integrated Facility	£15m - £20m	£5m - £10m	3-6 years
Total	£33m - £43m	£20m - £25m	

Table 22 Recommended Technology Development Opportunities

This investment, which the ETI is uniquely positioned to make, would deliver the following benefits to the UK economy:

- Internationally competitive solution to the challenge of community scale gasification technology,
- Technology that could lead to an internationally competitive position in the gasification gas clean-up market,
- Improved AD technology,
- Know how and demonstration of effective integrated waste to energy systems for wet and dry wastes with low costs and high yields.

The end goal of the programme would be to demonstrate the investment case in technology to satisfy a proportion of the 10,000 UK applications with export potential. These opportunities were validated by the ETI's Energy from Waste technology stakeholders on the 6th of June 2011, where the consortium and the ETI were guided to the value to the energy from waste and thermal processing industries from the ETI supporting further development in the integration of gasification systems.

Additionally, the project identified that the development of low cost heat networks, processes to covert syngas into chemicals or fuels and the pyrolysis of segregated materials for liquid fuel production are potential areas of opportunity to increase the value of the core technologies recommended for development.

Taking the above recommendations together, there is a clear opportunity to develop technologies to a TRL of ~6-7 within the EfW sector. This opportunity does not lie on the development of large-scale systems at the scale of cities as established technology exists and has been well deployed, but at the scale of towns and villages where the amounts of wastes processes are 50kt/yr or less. The next step of development of both thermal and anaerobic digestion technologies at this scale to overcome the current technical barriers requires system level engineering and optimisation, which the ETI is well placed to enable through the funding of facilities and multi-partner technology development programmes.

8 Glossary and abbreviations

Anaerobic Digestion: a natural process, which converts organic matter such as household food and garden waste, farm slurry, waste from food processing plants and supermarkets, into energy. The main products resulting from anaerobic digestion are biogas (a mixture of methane and carbon dioxide), which is very similar to natural gas, and digestate, a low level fertiliser.

Biogas: the mixture of gases produced by AD is called biogas. The main gas is methane (CH4) at around 60%, a colourless, odourless gas, and carbon dioxide (CO2) at around 40%. There will also be small amounts of contaminant gases, mostly hydrogen sulphide and ammonia. The precise make up of the gases depends on the type of feedstock and the type of AD.

Biomass: the term for substances, which have grown from animal or vegetable matter.

Calorific Value (energy): the quantity of heat produced by the complete combustion of a given mass of fuel, usually expressed in joules per kilogram.

Commercial & Industrial waste: controlled waste arising from the business sector. Industrial waste is waste generated by factories and industrial plants. Commercial waste is waste arising from the activities of wholesalers, catering establishments, shops and offices.

Digestate: the undigested remnants of the feedstock that bacteria cannot use and the remains of dead bacteria from the Anaerobic Digestion process. It contains valuable plant nutrients like nitrogen, phosphate and potassium and organic humus, so it can be spread on the land as a substitute for synthetic fertiliser.

Distributed energy: the supply of heating, cooling, and/or power, to customers of all scales including domestic or industrial, and is generated on or relatively near the site where it is used. It includes, but not limited to: combined heat and power (CHP); small scale onsite electricity technologies, such as small scale and micro hydropower, micro and small wind turbines and photovoltaics (solar PV); biomass, solar thermal, heat pumps (to generate heat); micro CHP and fuel cells (to generate heat and power); and, district heating as a means of transporting renewable or low carbon heat to multiple consumers.

Dry wastes: the consortium has defined for the purposes of this project, wastes with an average of 20% and a maximum of 40% moisture content.

Energy from Waste: the process of creating energy in the form of electricity or heat from the incineration of waste source and is a form of energy recovery. Most Energy from Waste processes produce electricity directly through combustion, or produce a combustible fuel commodity, such as methane, methanol, ethanol or synthetic fuels.

Fossil Fuel: any naturally occurring carbon or hydrocarbon fuel, such as coal, petroleum, and natural gas, formed by the decomposition of prehistoric organisms.

Gasification: is the sub-stoichiometric oxidation or steam reformation of a carbonaceous material to produce a gaseous mixture containing two or all of the following: oxides of carbon, methane and hydrogen.

Green House Gas: a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range.

Incineration: for the purposes of this study, it is considered a thermal treatment process that involves the combustion of the material. Often combined with energy recovery (through a steam cycle) for waste treatment – currently referred to as "Energy from Waste"

Landfill: means a waste disposal site for the deposit of waste onto or into land (i.e. underground).

Landfill gas: all gases generated from landfilled waste.

Methane: a chemical compound with the chemical formula CH_4, and the principal component of natural gas; a colourless odourless flammable gas.

Mechanical Biological Treatment: Combinations of waste treatment technologies, including mechanical sorting and biological treatment (e.g. composting, AD, biodrying etc). Order of processes and technologies varies, as such, many covered by this generic term. Is not a total waste treatment solution in its own right, and all or some of the material will require further treatment/disposal.

Municipal Solid Waste: all types of solid waste generated by households and commercial establishments, and which is collected usually by local government bodies.

Pyrolysis: the thermal degradation of a substance in the absence of any oxidising agent (other than that which forms part of the substance itself) to produce char and one or both of gas and liquid.

RDF (Refuse Derived Fuel): Usually refers to the segregated high calorific fraction of processed MSW.[34]

Sewage: water-carried wastes, in either solution or suspension that is intended to flow away from a community.

Solid Recovered Fuel: Floc material formed from dried and shredded residual waste, commonly following recyclables and biogenic fraction recovery. Produced to semi-defined standard, with final composition being dependant on waste composition, generally falling within customer-set energy content limits.

Sticktion: Inertial friction – resistance to initial movement caused by adhesive properties of lubricants (due to surface tension) to stationary surfaces; once overcome, lubricant acts to reduce friction.

Technology Readiness Level: systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology through nine levels.

Wet waste: the consortium has defined for the purposes of this project, wastes with greater than 80% moisture content.

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[34] http://ec.europa.eu/environment/waste/studies/pdf/rdf.pdf

AD – Anaerobic Digestion
A – Agricultural
BAT – Best Available Techniques
CBI – Confederation of British Industry
C&D – Construction & Demolition
CO_2 – Carbon Dioxide
C&I – Commercial & Industrial
CHP – Combined Heat and Power
Com- Commercial
CPI – Centre for Process Innovation
CV - Calorific Value (energy)
DE - Distributed Energy
DEFRA - Department for Environment, Food and Rural Affairs
DrMt- Dredging materials
EC - European Commission
EfW - Energy from Waste
ETI – Energy Technologies Institute
ES –Environmental Statement
EU – European Union
FRP – Flexible Research Project
GHG - Green House Gas
GJ - Gigajoule
GWP: Global Warming Potential
H_2S – hydrogen sulphide
H_2 - Hydrogen
IGCC - Integrated Gasification Combined Cycle
Ind- Industrial
IPCC - Intergovernmental Panel on Climate Change
kT - Kilo tonne, 1000 tonnes
kTpa – Kilo tonne per annum
M&Q- Mining and quarrying
MBT – Mechanical Biological Treatment
MRF – Municipal Refuse Fuel
MSW – Municipal Solid Waste
MWhr - Megawatt Hour
NPV – Net Present Value
ONS - Office for National Statistics
p.a – per annum
RDF – Refuse Derived Fuel)
SRF – Solid Recovered Fuel
SS – Sewage Sludges
TDO – Technology Development Opportunity
TOE - Tonnes of oil equivalent
TRL – Technologies Readiness Level
TWhr - terawatt-hour
UK – United Kingdom
WP – Work Package
WID - Waste Incineration Directive
YR – Year